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Influence of long-term episodic cyclic loading with rest periods on pipe-soil interaction

Influence des essais cycliques épisodiques à long terme avec période de repos sur l'interaction sol-pipeline

Zhechen Hou, Fauzan Sahdi, Christophe Gaudin & Mark Randolph
Centre for Offshore Foundation Systems, Ocean Graduate School, The University of Western Australia, Australia, zhechen.hou@uwa.edu.au

ABSTRACT: Steel catenary risers (SCRs) are pipelines widely used for transporting hydrocarbon resources from subsea fields to floating structures. The assessment of long-term fatigue life of SCRs, especially at the section close to the touchdown zone, where complex soil-fluid-structure interaction occurs, remains a significant challenge for designers. A key question that is currently causing debate is the evolution of the cyclic stiffness for riser-seabed interaction and the associated competing effects of soil remoulding with those of consolidation. The estimation of soil stiffness due to pipe movements is critical for fatigue assessment over the SCR operational life. This paper provides insights on soil hardening through reconsolidation, after initial cyclic soil remoulding. This was achieved by comparing the long-term soil stiffness evolution between a continuous cyclic test and episodic cyclic tests with intermittent rest periods. Test results show that soil stiffness recovers significantly due to soil consolidation during rest periods, but this recovery is less than that for a continuous cyclic test with the same elapsed test time. These results provide an improved understanding of pipe-soil interaction with rest periods during which consolidation occurs, and the subsequent influence on the long-term evolution of the cyclic stiffness.

RÉSUMÉ: Les pipelines verticaux (Steel Catenary Risers) sont des pipelines largement utilisés pour transporter les hydrocarbures des fonds sous-marins vers les structures flottantes. L'évaluation de la résistance à la fatigue à long terme des SCR, en particulier dans la zone de contact avec le sol, où se produit des interactions sol-fluide-structure relativement complexes, reste un problème de taille pour les ingénieurs. Une question clé qui fait actuellement débats est celle de l'évaluation de l'élasticité du sol et de son évolution a travers les effets de cisaillement et de reconsolidation. Cette élasticité est essentielle à l'évaluation de la fatigue tout au long de la durée de vie opérationnelle du SCR. Cet article donne un aperçu de l'augmentation to l'élasticité du sol par reconsolidation, après un premier cycle de chargement. Ceci a été réalisé en comparant l'évolution à long terme de la résistance du sol entre un test cyclique continu et des tests cycliques épisodiques avec des périodes de repos intermittentes. Les résultats des tests montrent que la résistance du sol augmente en raison de la reconsolidation du sol pendant les périodes de repos, mais que cette augmentation est inférieure à celle d'un test cyclique continu avec le même temps écoulé. Ces résultats permettent une meilleure compréhension de l'interaction entre les SCRs et le sol.

KEYWORDS: Pipe-soil interaction, soil remoulding, soil reconsolidation, episodic cyclic loading, rest period

1 INTRODUCTION

Steel catenary risers (SCRs) form an integral part of deep water oil and gas extraction, enabling hydrocarbon products from pipelines on the seabed to be transported to floating production systems. Fatigue life assessment of SCRs has been investigated extensively accounting for complicated pipe-soil interaction (Clukey et al. 2017), especially when SCRs interact continuously with the soil at the touchdown zone (TDZ). The SCR will interact cyclically with the near mudline seabed soil throughout its operational life (Randolph & White 2008, Randolph et al. 2011). Under ambient environmental loading on the SCR, the soil at the TDZ may soften during the initial remoulding stage. However, under prolonged cyclic SCR-soil interaction, the soil strength may also recover due to reconsolidation (Yuan et al. 2017). This changing nature of the seabed soil strength and associated stiffness throughout the SCR operational life adds to the uncertainty in SCR fatigue assessment.

Furthermore, the extent of soil strength recovery due to reconsolidation remains disputable between single gravity tests and centrifuge tests.

Long-term episodic cyclic tests were carried out in previous studies to simulate pipe behaviour; in such tests the cycles are intermittent with rest periods allowing for alternating remoulding and reconsolidation of the soil. In normally or lightly over-consolidated clay, previous centrifuge pipe episodic cyclic tests (Hodder et al. 2009) showed that the pipe-soil stiffness initially decreased due to soil remoulding (which can be exacerbated by water entrainment) during cyclic loading episodes; however, as the excess pore pressure generated during soil remoulding is dissipated during rest periods (i.e. reconsolidation), the pipe-soil stiffness can increase and even exceed the initial stiffness with repeated cyclic loading episodes and rest periods. Episodic centrifuge T-bar penetrometer tests in both kaolin clay and carbonate silt (Cocjin et al. 2014, Zhou et al. 2020a) also showed a steady-state strength of ~3 times the initial soil strength after alternate cyclic loading and rest periods. Other pipe tests under single gravity conditions in heavily overconsolidated Gulf of Mexico (GoM) soil, which was fully swelled after removal of a pre-consolidation stress between 85 and 89 kPa, showed soil strength increase at a relatively low level after overnight consolidation (Clukey et al. 2005), and the recovery degraded quickly after subsequent cyclic loading. Some results (Aubeny et al. 2015) have shown very little difference in initial stiffness values for a rest period of 17 days between cyclic loading episodes. Recent single gravity episodic tests in reconstituted natural GoM soil (Al-Janabi et al. 2019) also showed limited increase in soil resistance due to reconsolidation after hours of rest period, softening rapidly through subsequent soil remoulding due to cyclic loading. By contrast, T-bar tests in reconstituted normally consolidated GoM soil showed ~20% increase of the initial remoulded soil strength (Sahdi et al. 2021) after five episodes of cyclic loading interspersed with rest periods.

This paper extends previous studies by comparing the evolution of soil stiffness between episodic cyclic tests with intermittent rest periods and a continuous cyclic test carried out in a centrifuge in reconstituted kaolin clay (Hou et al. 2021). The combined effects on soil stiffness evolution, from both the remoulding stage generated by cyclic loading episodes and the reconsolidation stage arising from rest periods, are discussed.

2 EXPERIMENTAL PROGRAMME

2.1 *Centrifuge facilities*

The centrifuge tests were performed in the C72 beam centrifuge (Gaudin et al. 2018) at the Centre for Offshore Foundation Systems (COFS) of the University of Western Australia (UWA). A cylindrical strongbox was used in this test programme with dimensions of 895 mm in diameter and 700 mm in height. The sample was spun in the centrifuge at an acceleration level of 20*g* during both sample consolidation and testing stages.

2.2 *Model pipe*

To simulate an 'element' of SCR at the touchdown zone, the model pipe shown in Figure 1 was used in the centrifuge tests. The model pipe has an outer diameter (D) of 25 mm and a length (L) of 150 mm. At a centrifuge acceleration level of 20*g* during tests, the model pipe represents a 0.5 m diameter SCR. A load cell was used to measure the soil resistance during cyclic loading.

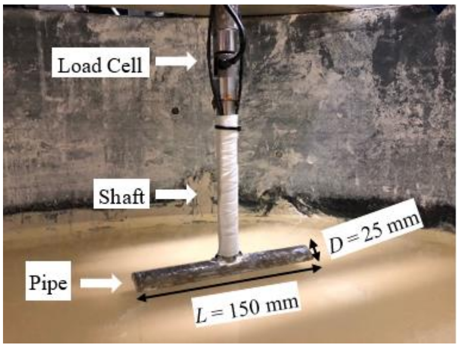

Figure 1. Model pipe illustration.

2.3 *Sample preparation*

Commercial kaolin slurry was mixed thoroughly at a targeted water content of 120% and was then de-aired for 2 days in a mechanical vacuum mixer. Subsequently, the de-aired slurry was poured into the strongbox in five successive layers, underlain by a fully saturated sand layer of 215 mm, acting as a drainage layer. The kaolin and sand layers were separated using a geotextile. The successive slurry layers were compressed under decreasing loads using a servo-hydraulic press, until each layer was fully consolidated. After full consolidation of the five layers, the sample was finally compressed again under a larger load. The duration of the final applied load was carefully controlled so that only partial excess pore pressure dissipation was allowed in the top ~50 mm soil layer in order to create a crust of approximately 1 m thick (prototype scale) at a centrifuge test acceleration level of 20*g*. The soil sample was then spun at 20*g* in the centrifuge until primary consolidation was achieved, which was ascertained by monitoring the pore pressure dissipation at the sample mid-height position.

A T-bar penetrometer (Stewart & Randolph 1994), 5 mm in diameter and 20 mm in length, was used to infer the undrained shear strength of the sample. Penetration rate for the T-bar penetrometer was set at 1 mm/s to ensure undrained conditions (Randolph & Hope 2004).

The undrained shear strength profiles from two T-bar tests are shown in Figure 2, where the monotonic undrained strength was corrected considering the influence of shallow embedment when the penetrometer is close to the mudline (White et al. 2010).

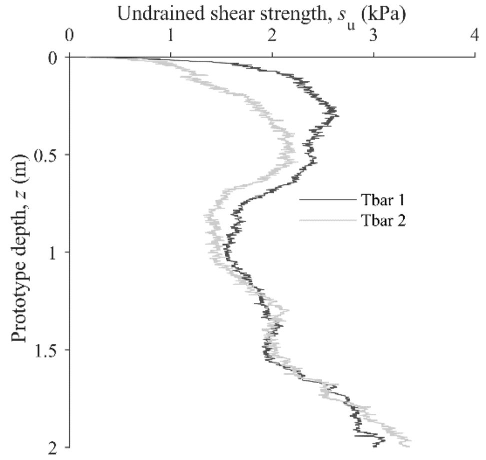

Figure 2. Profiles of undrained soil shear strength.

The peak soil undrained shear strength reaches ~2.5 kPa at a prototype depth of 0.25 m, reducing to ~1.5 kPa at 1 m depth, below which the strength increases linearly with depth at a gradient of about 1.5 kPa/m, which is typical of normally consolidated kaolin clay.

2.4 *Testing programme*

An episodic cyclic test was carried out in the centrifuge as detailed in Figure 3a, where w is the pipe invert depth throughout the test. This test was performed at an initial pipe penetration depth of 1D, which was followed by four cyclic loading episodes of 100 cycles with a peak-to-peak displacement range of $\Delta w_{max}/D$ = 0.02. Between adjacent cyclic loading episodes, the model pipe was held at the depth of 1D with an intermittent rest period of 1.5 hours in the centrifuge, representing a prototype resting time of 25 days in the field. A cyclic frequency of 0.1 Hz was maintained for all cyclic loading episodes, ensuring undrained loading conditions. In comparison, Figure 3b shows a continuous cyclic test (Hou et al. 2021), where the pipe was initially penetrated to 1D followed by continuous cyclic loading with peak-to-peak displacement amplitude of $\Delta w_{max}/D = 0.02$.

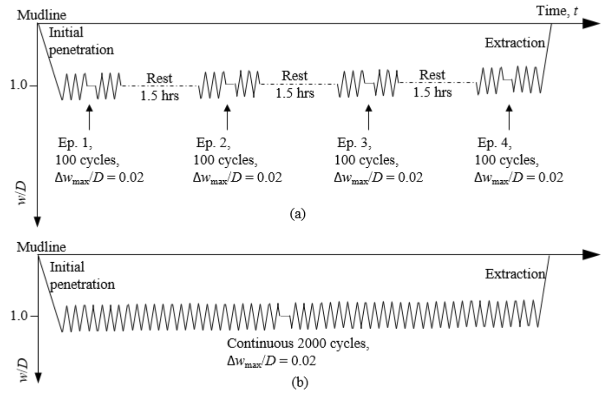

Figure 3. Test programme illustration for (a) episodic cyclic loading test (b) continuous cyclic loading test.

3 PIPE RESISTANCE INTERPRETATION

The total resistance measured by the load cell, F_t comprises the resistance from soil buoyancy (F_{bs}) and water buoyancy (F_{bw}), the resistance due to the soil strength (F_s) as well as the changing weight of the pipe as it moves radially within the centrifuge gravitational field (F_r). Here, only the resistance arising from the soil strength is taken into account and is calculated as:

$$F_s = F_t - f_b \times F_{bs} - F_{bw} - F_r \tag{1}$$

F_{bs} is augmented by a factor f_b in order to consider the enhanced buoyancy due to soil heave at shallow pipe embedment. This was taken as 1.5 at the mudline, decreasing linearly to 1.0 when a deep (full-flow) soil failure mechanism occurs at pipe invert depth of ~2.4D (Merifield et al. 2009).

The interpreted pipe-soil resistance q_s (calculated as F_s/DL) in each episode of the episodic cyclic test is plotted against normalised pipe depth in Figure 4. The initial 100 cycles of the continuous cyclic test (Hou et al. 2021) are also plotted in Figure 4a, revealing good agreement between these two tests at the beginning of the test.

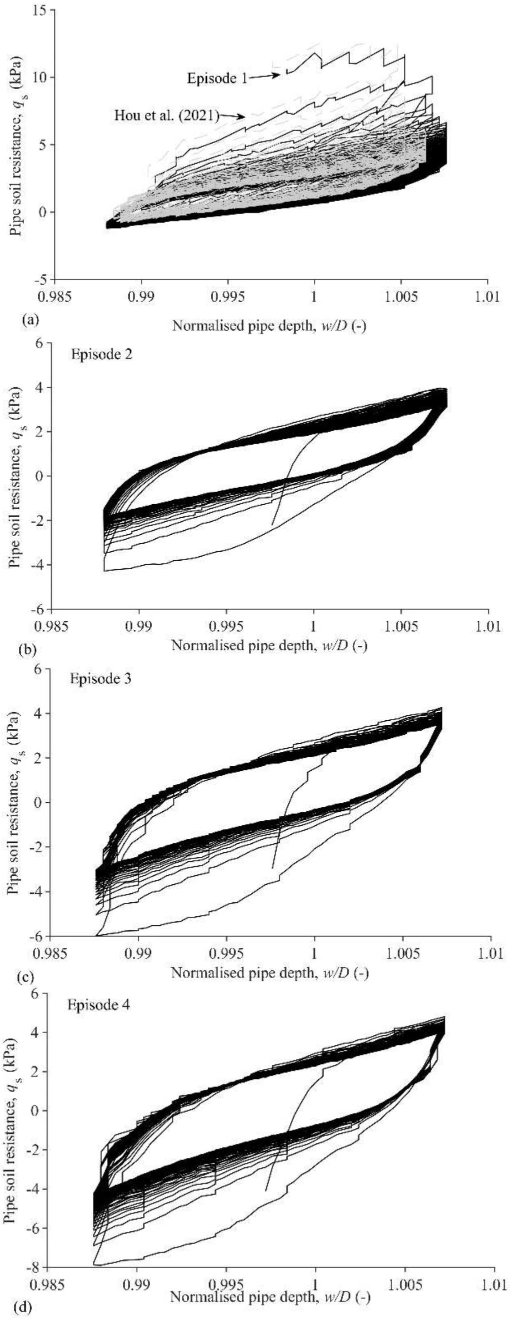

Figure 4. Cyclic pipe resistance of sequence tests for all episodes (a) episode 1 and initial 100 cycles from previous continuous cyclic test (Hou et al. 2021) (b) episode 2 (c) episode 3 (d) episode 4.

Figure 5 depicts the q_s obtained from the initial cycle (i.e. 1st cycle) and last cycles (i.e. 100th cycle) of all four episodes. After initial remoulding due to cyclic loading in episode 1, the q_s at the 100th cycle of episode 2 to 4 increases. This represents the increase of fully remoulded soil resistance due to soil reconsolidation in the intermittent rest period between cyclic loading episodes. This aspect is further explored from the cyclic evolution of secant soil stiffness in the following section.

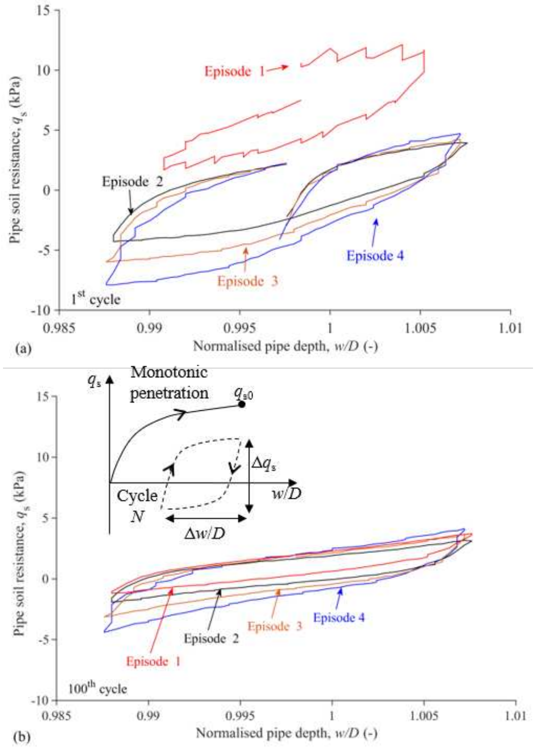

Figure 5. Cyclic pipe resistance for all episodes at (a) the initial 1st cycle (b) the last 100th cycle.

4 EVOLUTION OF PIPE-SOIL SECANT STIFFNESS

The evolution of the secant pipe-soil stiffness can be analysed by defining the normalised stiffness K_{sec} as:

$$K_{sec} = \frac{\Delta q_s/q_{s0}}{\Delta w/D} \tag{2}$$

where Δq_s is the change in pipe-soil resistance as the pipe is extracted upwards by Δw, and q_{s0} is the initial pipe penetration resistance at the initial load reversal point (see Figure 5b).

The unloading K_{sec} corresponding to $\Delta w/D$ = 0.015 during the pipe extraction phase is illustrated in Figure 6 as a function of the dimensionless time $T = c_h t/D^2$, where c_h is the horizontal consolidation coefficient taken here as 0.13 mm^2/s (Lehane et al. 2009, Hou et al. 2021), and of the equivalent time in cycle number, N.

For comparison purposes, the unloading K_{sec} resulting from a continuous cyclic test without rest periods (Hou et al. 2021) showed an initial decrease of K_{sec} values from 66.2 to 22.8 due to the initial soil remoulding. Due to soil reconsolidation with gradual dissipation of excess pore pressures, K_{sec} increases at a rate of ~7.5 per unit dimensionless time (ΔT = 1) from 22.8 to 50. In the episodic cyclic test, the soil was remoulded in episode 1 as indicated by K_{sec} reducing from 59.5 to 24. This agrees reasonably well with the initial softening phase in the continuous cyclic test. This decrease in stiffness by a factor of ~2.5 is similar to the kaolin sensitivity of 2.6 (Stewart 1992, Gaudin & White 2009). For episodes 2 to 4, the softening ratios, defined as the ratio of initial to remoulded K_{sec}, are 1.7 – 1.8, due to the limited consolidation time allowed during rest periods. Each intermittent rest period represents a prototype time of 25 days and a dimensionless time of ~1.1, which leads to around 84%

dissipation of excess pore pressure based on estimation of consolidation around pipelines (Gourvenec & White 2010). From episode 2 to 4, the initial and remoulded K_{sec} values at the beginning and the end of the cycles in each cyclic episode increase by a factor of ~1.2 – 1.3 times, from 44.2, 54.6 to 66.6 and 25, 32 to 39 respectively. The initial K_{sec} values from episode 2 to 4 are always higher, yet the remoulded K_{sec} values are lower, than that in the reference continuous cyclic test at the same dimensionless time. The final remoulded K_{sec} value (39) at the end of episode 4 is about 1.6 times the final remoulded value (24) of episode 1, indicating an increasing rate of ~3.9 per unit dimensionless time ($\Delta T = 1$); this is approximately half of that in the continuous cyclic test. This can be attributed to changes in pore pressure dissipation rate and differences in the effective stress history due to the different loading regimes. This is explored further in the following section.

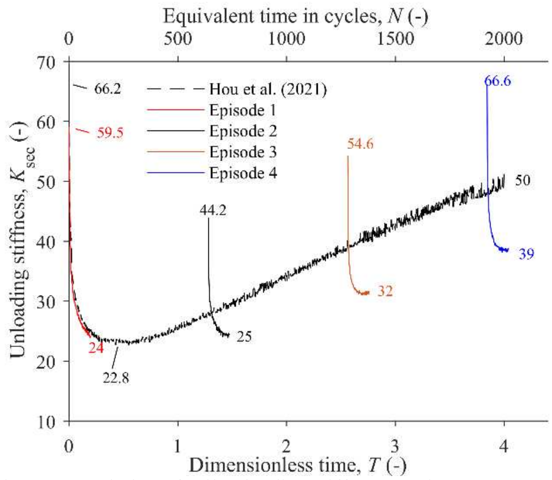

Figure 6. Evolution of soil unloading stiffness K_{sec} in tests.

5 CONCEPTUAL STRESS PATHS

The change of soil undrained strength is governed directly by the change in effective stress and specific volume (Schofield & Wroth 1968). Figure 7 presents the conceptual effective stress paths (ESP) for both episodic and continuous cyclic tests.

The initial stress states (starting point O) are identical for both the episodic cyclic test and the continuous cyclic loading test. During the initial remoulding stage of the soil, the effective stress reduces due to the accumulation of excess pore pressures under undrained shearing as indicated from rapid degradation of strength in previous penetrometer tests (Einav & Randolph 2005, Sahdi 2013, Zhou et al. 2020b). Hence the effective stress path (ESP) moves horizontally (under constant volume condition) until it meets the fully remoulded state line (RSL).

In the long-term continuous cyclic test, the ESP then moves along the RSL line (O-A-B_1-C_1) with gradual reconsolidation of soil because of the additional cycles and associated shearing. By contrast, in the episodic cyclic test, soil reconsolidation during a rest period follows the unloading-reloading line (URL) with a slope of κ (since there are no additional shearing events) until the next cyclic loading episode starts from point B_2. Hence, the soil stiffness at the start of episodes 2 to 4 is higher compared to that in a continuous cyclic test (σ_v' at B_2 is higher than that at B_1 on the RSL).

By contrast, the remoulded stiffness values at the end of episodes 2 to 4 are consistently lower than the corresponding values for the continuous cyclic test (see Figure 6). This may result from the further soil contraction due to pore pressure dissipation during a continuous cyclic event compared with the episodic cyclic test at the same dimensionless time, i.e. the specific volume at B_1 is lower than that at B_2. During the subsequent cyclic loading episode, the ESP moves from point B_2 until it reaches again the RSL at C_2, where σ_v' is lower than at C_1 (moved from B_1 along RSL) in the continuous cyclic test.

The above conceptual analysis indicates that the change in strength due to episodes of shearing and rest may be described using a critical state soil mechanics framework.

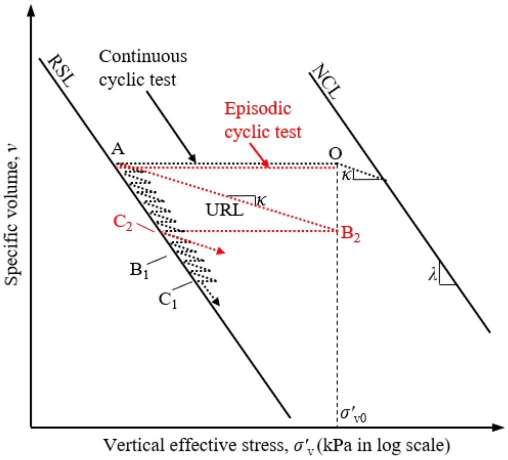

Figure 7. Effective stress path for episodic cyclic loading with rest period and continuous cyclic loading test.

6 CONCLUSIONS

Cyclic pipe-soil interaction in clay was investigated in this paper, exploring the influence of different loading regimes, in particular differences between episodic cyclic tests and a continuous long term cyclic test. The study revealed significant recovery of soil strength or stiffness in episodic cyclic tests and highlights the difference in the soil strength recovery rate between each episodic cyclic test and the continuous cyclic test.

Results from continuous cyclic loading tests showed typical initial remoulding and reduction in pipe-soil stiffness, followed by a continuous stiffness increase due to consolidation. In contrast, episodic cyclic test in the centrifuge showed regain in stiffness during each resting period and softening during the subsequent cyclic episode. Typically, stiffness recovery after the reconsolidation period in the episodic cyclic tests is initially higher than for the continuous cyclic test at the same dimensionless consolidation time. Correspondingly the stiffness decreases rapidly during each cyclic episode, leading to lower remoulded stiffness than for the continuous cyclic test. The rate of increase of episodic remoulded values versus dimensionless time is half that in the continuous cyclic test.

These observations can be readily described within the critical state soil mechanics theory, providing insights into how designers can account for the whole loading history in evaluating SCR fatigue life.

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