Planning the preloading procedure to account for rate-effects in clays

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ABSTRACT

When jacking up in clay soils, the rate-dependence of the soil is observed when attempting to hold the target preload. Four-legged construction jack-ups perform preloading using the principle of load redistribution between diagonally opposite leg pairs to achieve penetration and reach the target preload. During the final phases of the jacking process, when the preload is "reached", a reduction of the leg load occurs, and the load must actively be brought back to the target preload value. In clay soils this leads to further penetration and multiple cycles are required. This "iterative process" can result in large additional, creep-like spudcan penetrations (up to several meters at some sites) and results in large jacking times during, for example, the construction of an offshore wind farm. The phenomenon is well known and mentioned in the InSafe JIP guidelines but detailed guidance on the causes and possible mitigation measures is not available. In order to gain more insight into this phenomenon and as a continuous effort to optimize processes, available jacking data from GeoSea's Innovation vessel at two sites (one with predominantly clay and the other sand conditions) have been compared and analysed in detail. Several possible mechanisms were hypothesized and investigated but the conclusion of the work was that the viscous and rate-dependent properties of clay were the most likely cause of the observed additional penetrations. Based on this study, an alternative "overshooting" jacking procedure, which reduces the total time required for jacking in clay locations, was proposed and successfully applied during construction of an offshore wind farm.

KEY WORDS: jack-up vessel, clay, spudcan penetration, creep.

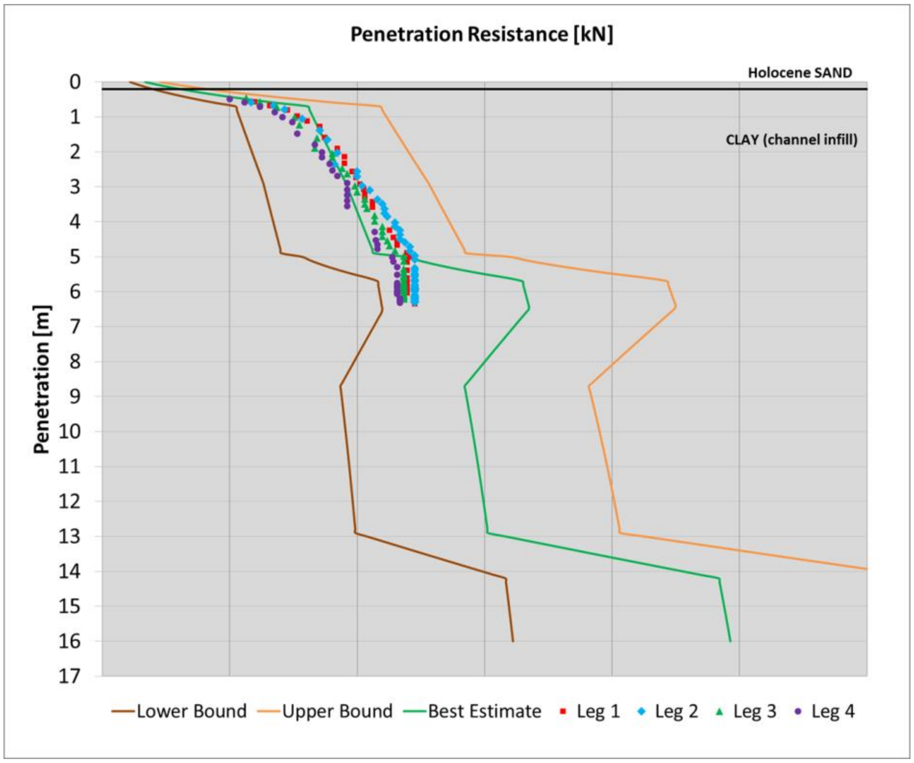
INTRODUCTION

When jacking up in clay soils, the rate-dependence of the soil is observed when attempting to hold the target preload. Four-legged construction jack-ups perform preloading using the principle of load redistribution between diagonally opposite leg pairs to achieve penetration and reach the target preload. During the jacking process, when the preload is "reached", a reduction of the leg load occurs, and the load must actively be brought back to the target preload value through further penetration.

In clay soils this leads to further penetration and multiple cycles are required. This "iterative process", intended to maintain a constant preload, can result in large additional, creep-like spudcan penetrations (visible on the leg penetration curve in Figure 1) of up to 1.2m at certain locations and is suspected to increase the potential for higher Rack Phase Differences. Additionally, this also results in large jacking times which become significant, when considering multiple jacking locations as required for the construction of an offshore wind farm.

In order to gain more insight into this phenomenon and as a continuous effort to optimize processes, available jacking data from two sites, an offshore wind farm project site with Channel Infill and Boulders Bank clay and a port location, with sand conditions, have been analysed and compared. Published literature on model tests and time-dependent soil behaviour have been reviewed to establish the cause of the observed additional penetrations, and finally an alternative jacking procedure is proposed, intended to reduce the overall jacking time and potentially reduce the risk on excesive rack phase differences.

Figure 1: Recorded jacking log at a site displaying additional penetration while holding preload holding



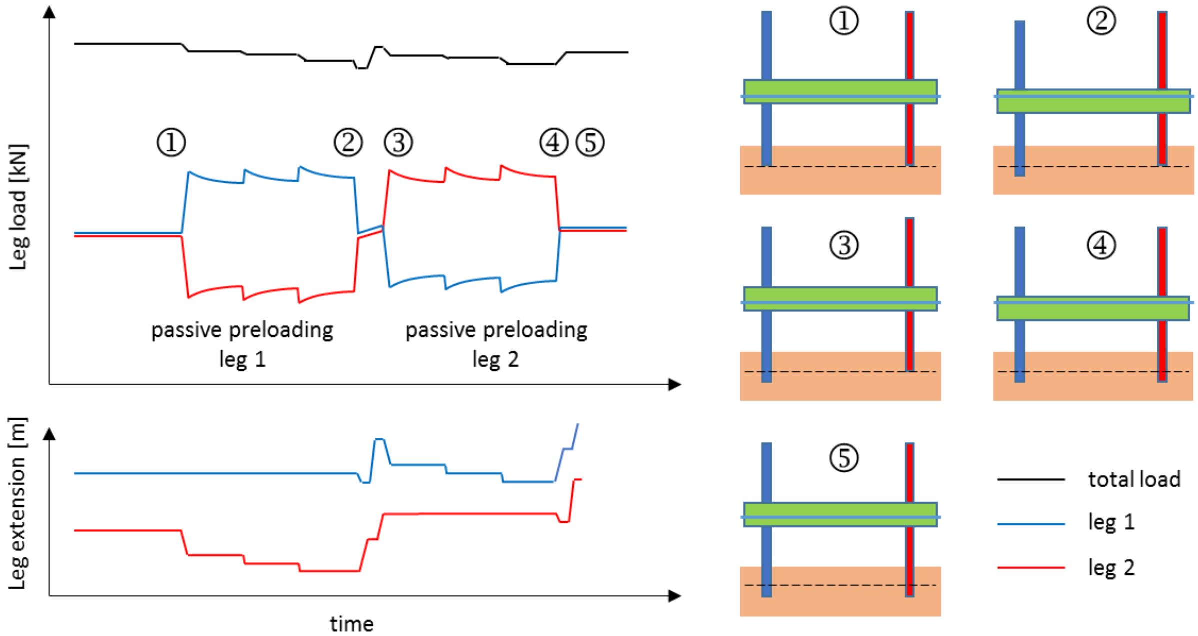
PRELOADING PROCEDURE

A 4-legged jack-up vessel will preload the footings by loading alternately diagonally opposing leg pairs while decreasing the draft gradually. As illustrated in Figure 2 the load is gradually increased in this way. Preloading of a rack and pinion vessel can be either done actively (by increasing the load on the legs by increasing the torque of the drive motors) or passively (by releasing the brakes on the opposite leg pair). In the latter case the leg extension of the loaded legs will be constant and the unloaded legs will be retracted (without ever loosing contact with the soil), additional penetration will thus lead to an increase in buoyancy. Only the passive preloading will further be considered in this article.

Figure 2 shows the passive preloading procedure schematically. One leg pair (called the passive leg pair, labelled “leg 1” in Figure 2) is loaded by releasing the opposite leg pair (labelled “leg 2” in the figure). This results in load transfer to and penetration of the passive leg pair (phase ① – ②). The load is typically maintained for 5 to 10 minutes. During this interval, the operator will usually retract (release) the unloaded leg pair several times in order to maintain the load on the passive pair. For both cycles in Figure 2, only two corrections are illustrated, but in reality up to 5 or 6 may be required per cycle (see Figure 7). After this, the loads on all four legs are equalized and the deck is raised by adjusting the extension of all four legs as required (phase ② – ③), before starting the passive preloading cycle of the other leg pair (phase ③ – ④).

Each time an active leg pair is released (controlled by the operator), to apply load on the passive leg pair, the hull is sliding down over the active (retracting) leg pair, pushing the passive leg pair further into the soil (change from ① to ②). In between the corrections, the leg extension of all legs remains constant, and yet a gradual load transfer from the passive leg pair to the retracting leg pair is observed, prompting another correction. The accumulated effect of all these retractions is an additional spudcan penetration of up to 1.2m at some locations.

Figure 2: Schematic sketch of the passive preloading cycle



LITERATURE REVIEW ON RATE-EFFECTS DURING JACKING OPERATIONS

Houlsby and Martin [1] conducted model scale tests of spudcan penetration in overconsolidated kaolin clay. When penetration was stopped, the load immediately dropped by 11%. This loss of load was attributed to the rapid dissipation of transient pore pressures in the soil just beneath the footing and to creep behaviour of the soil skeleton. It was possible to restore the load to its original peak value, and maintain it at this level, by using a simple feedback control loop to generate additional vertical penetration. These observations are remarkably similar to the behaviour of jack-up legs discussed in this paper.

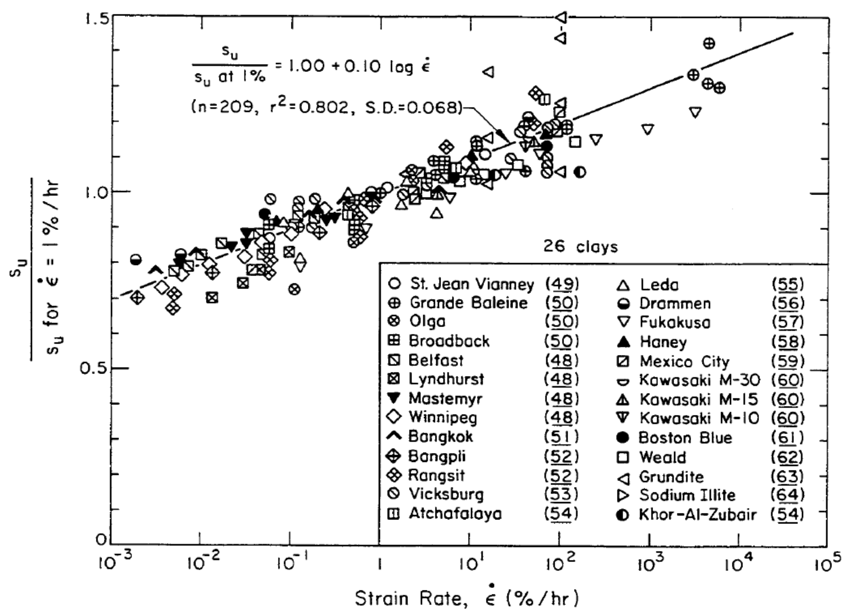
Hossain et al. [2] have analyzed case histories from 14 different jack-up locations (3-jegged jack-ups) in the Gulf of Mexico, predominantly normally and lightly overconsolidated clay (i.e. very large spudcan penetrations generally in excess 30m). At some sites, an additional settlement of 1–4m occurred while holding the final preload for a few hours, in particular where the seabed consisted of stronger clay. The authors suspect that the soil backflow process might have been delayed by the leg bracings, and hence, the cavity would have remained open for greater penetration depths. Subsequent sudden (not gradual) collapse (backflow) over the spudcans caused an increase in load on them, and caused further penetration of the leg. In addition, quicker accumulation and consolidation of the backfilled soil over the waiting period (usually up to 4 h) may have contributed as well. The authors do not believe that this 1m–4 m settlement was caused by creep.

InSafe JIP [3] guidelines state that in some soils significant spudcan penetration may occur while holding the preload. This can occur in soil with high plasticity due to viscous effects and consolidation, or in partially drained soils which may lose strength with time while under load, particularly in cases where the rate of increase of resistance with depth is very low.

TIME-DEPENDENT SOIL BEHAVIOUR

Clays exhibit shearing resistance which is a function of strain rate. This can be high during spudcan penetration, quickly reducing to zero when jacking is stopped. In general, each log cycle increase in strain rate is accompanied by approximately 10 percent increase in undrained shear strength, as demonstrated by the data shown in Figure 3.

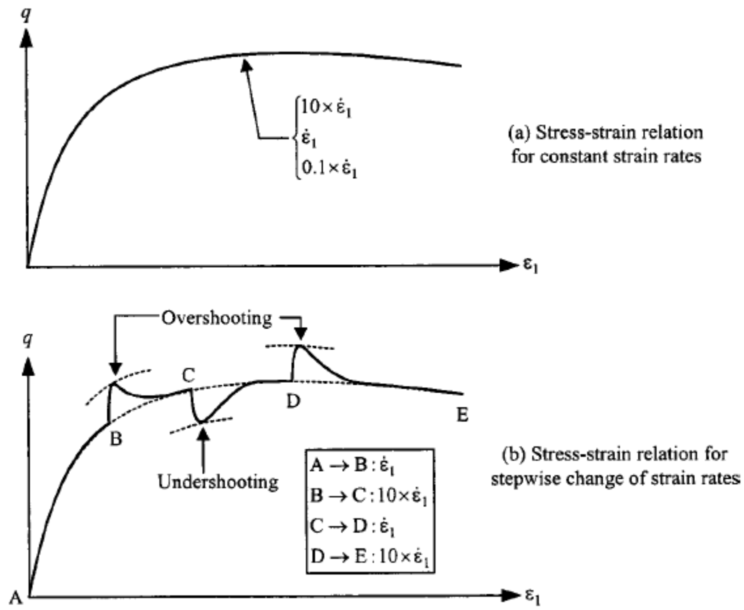
Figure 3: Influence of strain rate on undrained shear strength [4]



The effect of rate-dependent strength on spudcan penetration resistance in clay has been studied in detail by Hossain and Randolph [5]. The effects of rate-dependency were found to be significant, although partially compensated by the effect of strain softening. Nonetheless, a higher penetration resistance should be expected for higher spudcan penetration rates, regardless of the effect of strain softening.

Drained experiments on sands have shown that the shearing resistance is independent of the strain rate in steady strain rate conditions but do temporarily vary if the strain rate is changed in a step-wise manner, as shown in Figure 4. It may therefore be expected that the viscous response observed in clays is absent when jacking up in sand as long as free drainage occurs. In some materials (fine sands and silts, carbonate soils) the pore pressure changes during jacking may result in increases or decreases in strength while holding preload.

Figure 4: Schematic diagrams illustrating the rate-dependency observed for sand (drained) [6]



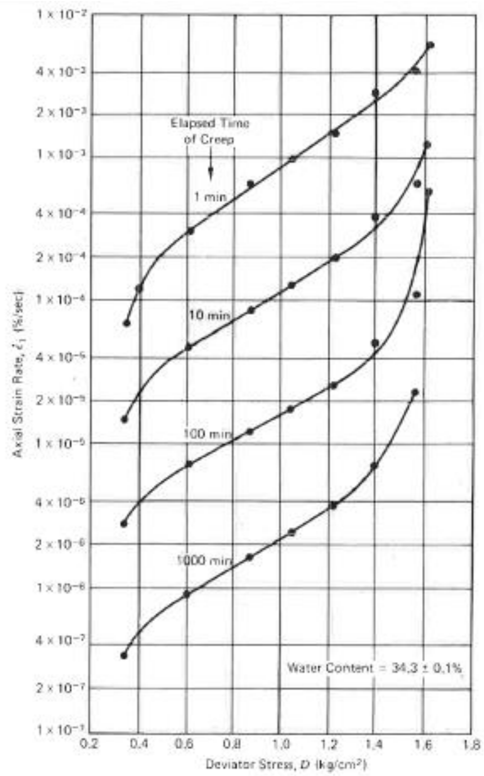
(a) The stress–strain relation for different constant strain rates coincide for the three strain rates and (b) temporary over- and undershooting due to stepwise change in strain rate

Another consequence of the viscous behaviour of soil is creep - subjected to a constant load, it deforms over time. The inverse phenomenon, termed stress relaxation, is a reduction in stress over time after a soil is subjected to a particular constant strain level. Creep and relaxation are two processes attributed to the same phenomenon, that is the development of permanent deformation associated with time-dependent changes in soil structure [7].

Creep and relaxation are usually important in problems where long term behavior is of interest, such as long-term settlement, deformations of or movement of earth structures. While the most common form of creep is secondary consolidation, measured in the oedometer laboratory test, this is related to volumetric deformation at stress states far away from shear failure. It usually takes place over long time scales of several times the consolidation time. In shear tests, creep manifests itself as the development of time-dependent shear strains. This can be studied using triaxial and direct shear tests, as for example shown in Figure 5. Such triaxial or direct creep tests are much more representative than oedometer tests for stress paths relevant to spudcan penetration in clay, which is predominantly a shearing process at quasi-continuous failure, in undrained conditions.

It can be observed from Figure 5 that at stresses approaching the strength of the material, the creep strain rate becomes very large and signals the onset of failure (at 1.6kg/cm² or approximately 160kPa in Figure 5). Conversely this implies rapid relaxation rates at shear stresses close to failure.

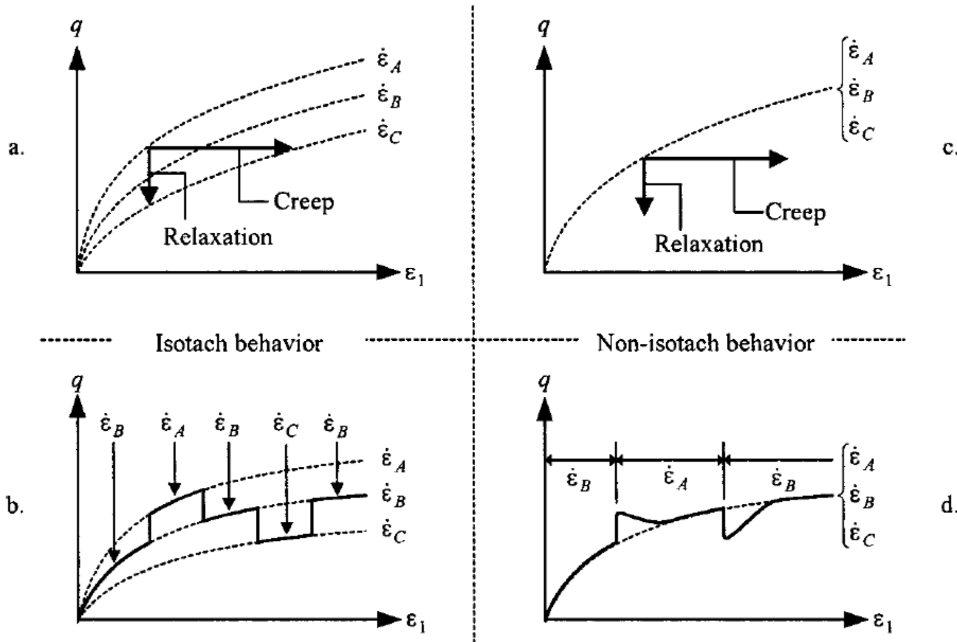
Figure 5: Undrained creep strain rate of remoulded illite [7]



For clays, it is widely accepted that the phenomena of creep, relaxation and strain-rate are governed by the same basic time-dependent mechanism (viscous response) and that there is a unique relationship between the stress, strain and strain rate (or time). This unique relation is denoted ‘‘isotach behavior’’ or “the correspondence principle” and has been established after analyzing results from a wide range of oedometer and triaxial tests on different natural clays [6]. This means that for example, creep and relaxation properties can be obtained by means of constant rate of strain (CRS) tests and vice versa. This is generally not true for sands, and therefore, their behavior is labelled ‘non-isotach’. Both models are illustrated in Figure 6.

For completeness, consolidation and thixotropy can be mentioned in the context of time dependent behaviour. They are not discussed further as they are not believed to be significant causes of the observed jack-up behaviour.

Figure 6: Isotach and non-isotach behaviour [6]



Isotach behavior is observed in clay for (a) creep and relaxation and (b) stepwise change in rate. Non-isotach behavior is observed in sand for (c) creep and relaxation and (d) stepwise change in rate.

DATA ANALYSIS

Available data for jacking operations with the Innovation at two locations were reviewed and analyzed in detail in an attempt to isolate the soil response in the data. The first location is a wind turbine location at an offshore wind farm site with Boulders Bank clay (Location A). This location represents a typical example of deep spudcan penetration in clay, with the final penetration varying between 3 to 6m for the different legs. Significant additional penetration during holding of the preload was observed. The second set of jacking data is from a port location, in sandy soil conditions and where no significant rate-dependent phenomena were observed (Location B). A general comparison of the two locations is made in Table 1.

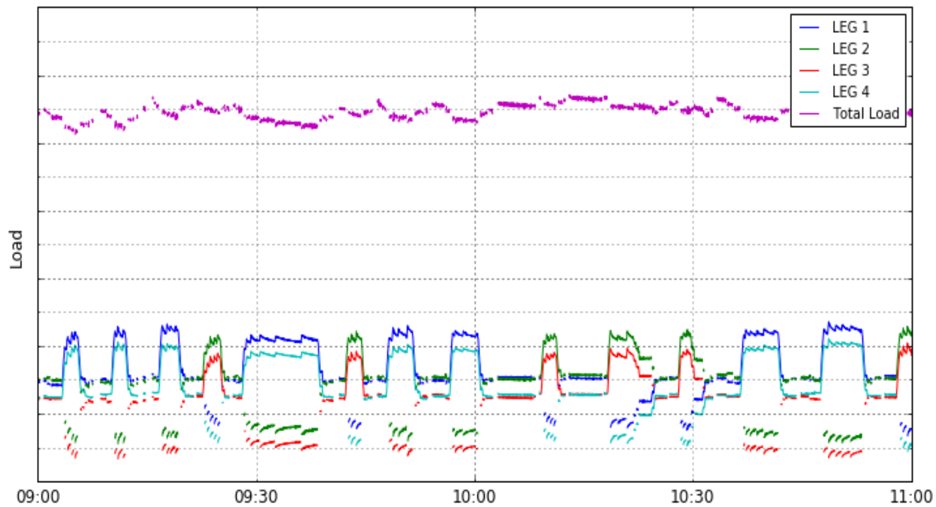
Table 1 Comparison of investigated jacking locations

	Location A	**Location B**
Location type	offshore wind farm	quayside
Soil conditions	mostly stiff Boulders Bank clay (60-90kPa), overlain by 1m of sand	sand
Water depth	18 m	11 m
Final penetration	3 – 6m	0.3 – 0.4m

The available data for both locations includes manual records of leg penetration and automatically recorded data from the SCADA system, such as GPS coordinates, vessel position and heading, and data from the jacking system (Rack Phase Values, leg load measurements and leg extension). The available data was used to reconstruct a detailed picture of the jacking sequence, the applied loads on the legs and ultimately the spudcan response to those loads.

An extract of the actually measured jacking data on Location A is shown in Figure 7. It shows a small but continuous increase in leg penetration during the load cycles if the leg pairs.

Figure 7: Extract of jacking data at Location A in clay



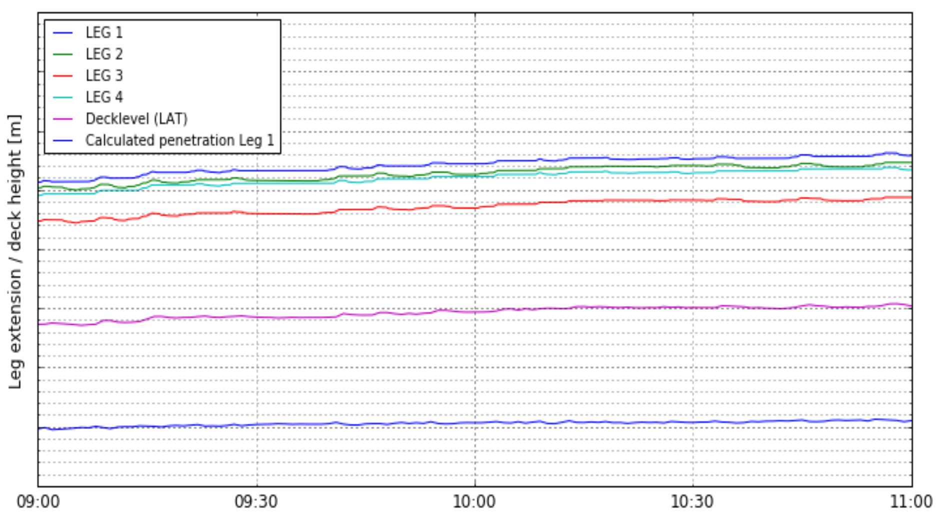


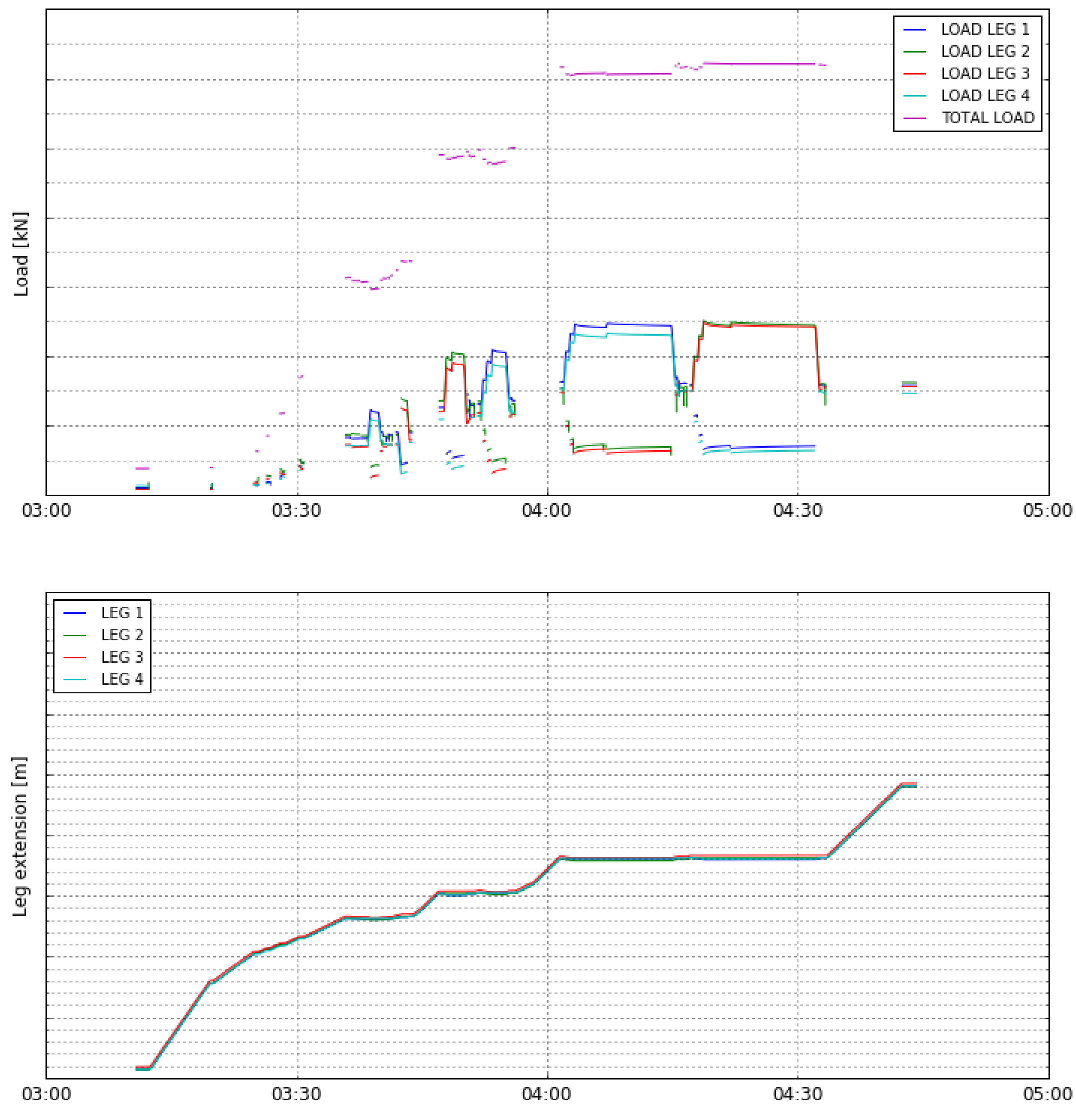
Figure 8 shows the jacking data for a jacking operation at the port location (Location B). Both figures show a two hour interval in the final stages of the preloading process. It can be noted that the total duration of the jacking procedure at Location B is a lot shorter than at Location A. At Location B the target preload is reached after only 6 loading cylces on the diagonally opposite leg pairs. During cycle 5 and 6 the load is maintained for approximately 15 minutes, requiring just a single additional retraction, something which was only possible for the very last few cycles at clay location. The preload is thus reached and maintained in a short time period, firstly because the total penetration is small (0.3 – 0.4m), but also because the sandy soil conditions do not lead to the relaxation behaviour observed in clay.

DISCUSSION

In the experiments conducted by Houlsby and Martin [1], the reduction of load was partly attributed to the rapid dissipation of transient pore pressures in the soil just beneath the footing. At prototype scale, only very little pore pressure dissipation will take place during a few hours in clay. However, for the majority of the locations at the investigated site, the clay units are covered by Holocene sand. If a sand plug is pushed down by the penetrating spudcan, some consolidation within this sand plug may occur when the penetration is stopped. Although this may contribute to the observed additional penetration, we estimate that this may only offset the recorded values by magnitudes in the order of 0.1m at most. Similarly, significant drained creep (secondary compressibility) is not expected within the timescale of the observed load reduction (hours).

Hossain et al. [2] suggested that sudden backfill of spudcan penetration cavities may have caused an additional penetration of 1-4m at some of the locations they studied. Total spudcan penetration at these locations was generally in excess of 30m, and in view of the significantly smaller spudcan penetrations of the Innovation at sites comprising firm to stiff clay, it is very unlikely that backfilling has caused the additional penetration.

Figure 8: Overview of jacking data during jacking at Location B



Cyclic loading may play a role, as during passive preloading, which alternates between leg pairs, the spudcans are subjected to a relatively large number of large-amplitude load cycles. As the leg is preloaded, the soil is loaded up to its bearing resistance. Unloading of the spudcan (because the other leg pair is preloaded), leads to relatively large amplitude, one-way cyclic loading. This low frequency cyclic loading could degrade the soil strength, increasing the likelihood and amplitude of additional penetration. Even if this may contribute to the observed cyclic ratcheting behaviour, it is not considered the main cause of the observed additional penetrations, as it offers no explanation for the observed load reduction when holding the preload. Moreover, it may be partly counterbalanced by thixotropic regain of soil strength following the intense remoulding that takes place during installation.

During review of the preloading data, it was established that the observed load transfer happens with very limited displacement of the spudcans (occurring on the unload-reload curve), the leg or the hull. This phenomenon thus complies with the definition of stress relaxation, and is considered to be soil-related.

The shear strength is fully mobilised below the passive legs as they penetrate (i.e. they are in a failure state) and therefore experiences rapid relaxation when penetration stops (since creep or relaxation rate is dependent on the distance from the failure surface). The soil below the active legs is subjected to much lower stresses, resulting in a net load transfer from the passive leg pair to the retracting leg pair. Structural relaxation of the vessel cannot be excluded as a contributing factor, but will happen much faster than in the relaxation time scales observed.

Upon re-loading of the passive leg pair, the soil response is not perfectly elastic, and a small but non-zero displacement is required to re-mobilize the previously reached capacity or soil resistance, giving rise to behaviour similar to cyclic ratcheting. This can also be understood in the context of the isotach model, as the spudcan is now moving on a leg penetration curve corresponding to a lower shear strain rate, or a lower spudcan resistance for the same penetration.

The combination of the following two phenomena are thus believed to cause the observed additional penetration:

- Load redistribution from the passive leg pair to the retracting leg pair due to stress relaxation in the soil, and
- Small, but non-zero mobilization distance required to bring the load on the passive leg pair back to the preload value

Both effects are amplified as the spudcan is always close to its bearing capacity, meaning that the stresses in the soil are close to the shear strength. The resulting overall load-penetration behaviour is very similar to a creep process - additional spudcan penetration is observed under the quasi-constant preload.

To further assess the plausibility of this mechanism, the observed load relaxation rates are compared to rates measured in laboratory tests on soil samples and model spudcans. Table 2 compares estimated relaxation rates from the following sources:

- Undrained creep tests on Illite clay. Measured creep strain rates as a function of the applied deviator stress are shown in Figure 5. Illite is one of the most common clay minerals and has a plasticity index of 20-50%. The creep strain rate measured at high deviator stress and shortly after beginning of the test (0.004 %/second) has been converted into an equivalent relaxation rate, by multiplication with the undrained Young's modulus. A range of E_u/S_u of 200 to 500 has been considered.
- Laboratory model tests on a 100mm spudcan in Kaolin clay, reported in [9]. Load relaxation of 10 – 15% was observed when the driving motors were stopped. Although the author reports this drop as 'immediate', the graphs suggest that the reduction took 3-6 seconds.

- Measured relaxation rates in the field at locations A and B. The measured load reduction rate has been divided by the spudcan area to give a stress relaxation rate with units of kPa/s. A few randomly selected instances at Location A showed relaxation rates of 1 - 1.3 kPa/s, over approximately 30 seconds. Over the same time interval, the relaxation rate at Location B was approximately 10 times smaller (0.1 – 0.25kPa/s).

Although the different estimated relaxation rates in clay are in good agreement, there is significant uncertainty on the estimated values, and should only be considered a very rough comparison. Furthermore, the relaxation rate under triaxial conditions is not solely representative of the stress conditions under the penetrating spudcan. It should also be noted that the load relaxation is expected to follow a logarithmic decay law. The relaxation rates shown in Table 2 are average relaxation rates near the start of the relaxation process and are expected to reduce with time.

Nonetheless, the data was considered convincing enough to propose the alternative, remedial jacking procedure described in the next section.

Table 2 Comparison of estimated relaxation rate, immediately after start of relaxation

	Illite creep test	Spudcan model test [9]	Innovation at Location A	Innovation at Location B
Measurement type	Creep strain rate in triaxial test	Load reduction rate on model spudcan	Load reduction rate on spudcan	Load reduction rate on spudcan
Soil type	Remoulded Illite	Kaolin	Channel Infill Deposit (clay)	Sand
Undrained shear strength	80 kPa	10 – 15 kPa	60 - 90 kPa	-
OCR	-	> 100		-
Plasticity	-	-		-
Load change	-	45.5 N	400 - 600t	100 t
Approximate time period	-	3-6 s	± 30 s	± 30 s
Relaxation rate	0.5 – 1.5 kPa/s	1-2 kPa/s	1 – 1.3 kPa/s	0.1 – 0.25 kPa/s

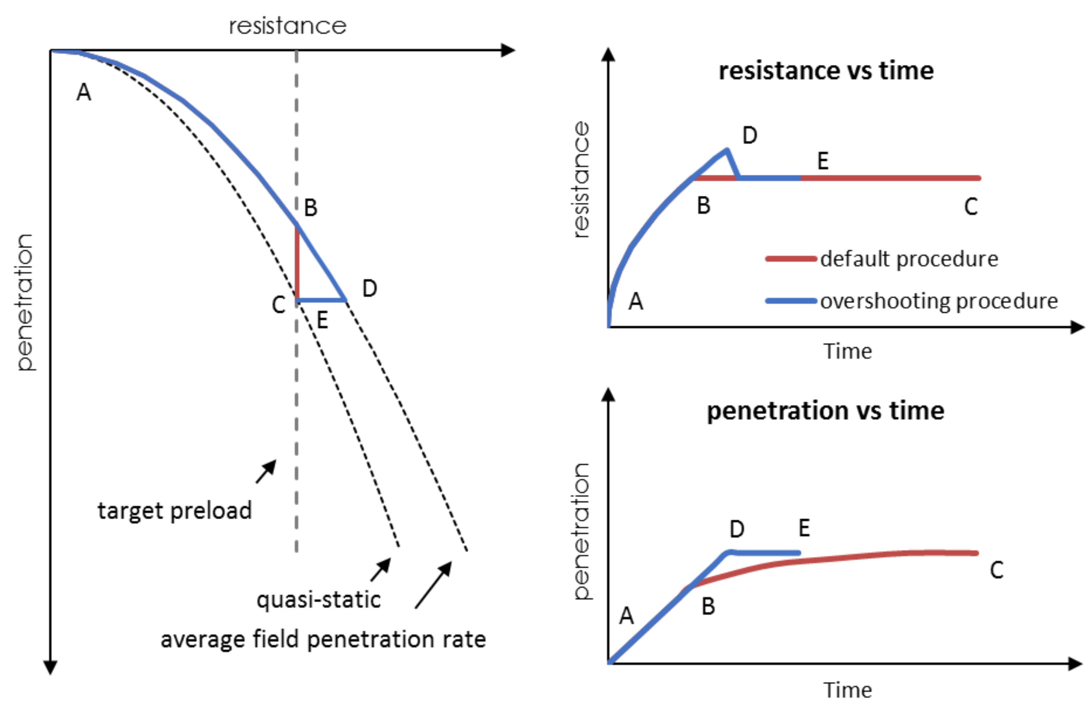
APPLICATION TO THE JACKING PROCEDURE

The spudcan resistance in clay has been shown to be rate-dependent. Based on results presented by Hossain and Randolph [5], the resistance at an average field penetration rate is estimated to be 10-15% higher than the quasi-static resistance.

Once the preload is reached and the spudcan is stopped (see section A – B in Figure 9), this gives rise to quite rapid load relaxation of the soil, which the operator corrects by increasing the load on the spudcan again. This process results in a creep-like additional spudcan penetration, and it may take a long time before the spudcan response is stabilized (section B – C in Figure 9 and section between 5 and 6.2m in Figure 1). In sands, the rate dependency is much smaller and additional penetration is generally not noted.

If the required target preload is overshot by 10-15% (point D) then the spudcan is brought to the depth which would have been reached by the creep-like additional penetration under the target preload-value. This alternative jacking procedure is sketched in Figure 9 (blue line).
This makes it possible to reach the end point (point C) of the standard procedure more quickly. Once the load is reduced from the overshoot to the target preload value (point D to E), it is likely that the preload can be sustained without additional penetration (and load cycles), as it is now located on the quasi-static leg penetration curve. This may seem to contradict the isotach hypothesis, which states that the relationship between resistance, deformation and time is unique, but the essential difference is that the step from point D to E is achieved by actively removing the load on the spudcan, not by (slow) relaxation in the soil.

Figure 9: Spudcan penetration and resistance – default and overshooting procedure



The overshooting procedure was tested on a recent project and found to work as expected, resulting in significant time savings.

The overshooting procedure is promising but it does require a loading capacity higher than the target preload, which is not always available. In layered soil conditions including clay-over-sand-over-clay it could also lead to excessive penetration when the peak punch-through load is exceeded unintentionally during overshooting. The required amount of overshooting needs to be determined on a site-specific basis.

CONCLUSIONS

A detailed analysis of a jacking case history has demonstrated that the rate-dependent soil response is consistent with the limited representative laboratory data. The cause of the additional penetrations observed while holding the preload are due to:

- Load redistribution from the passive leg pair to the active leg pair under constant leg extension due to stress relaxation, and

- The stiff response (small, but non-zero mobilization distance) required to bring the load on the passive leg pair back to the preload value.

The rate-effects of the soil response were used to develop an overshooting procedure to obtain the target preload more easily. The new approach was tested on a recent project and worked as expected.

There is still further optimization possible for the preloading procedure but this would require site specific laboratory testing and further specific research to confirm the provisional conclusions reached in this study. For example, the following specific analyses could be considered:

- Laboratory soil element testing (triaxial relaxation tests at high deviator stress) on representative clay samples;
- Scale model testing of spudcan penetration in artificial or real clay specifically focussed on the active/passive character of loading for construction jackups; and
- Numerical study of stress conditions below the spudcan, potentially including a material model which includes time-dependent behavior.

Furthermore, the requirement to keep the preload on the spudcan for a specified time period (e.g. 30 minutes) without additional penetration could be re-evaluated in line with recommendations from the InSafe JIP [3]. A systematic review of the dependency of the relaxation rates on the clay properties could provide the basis for establishing a criterion for allowable rate of additional penetration or load relaxation in lieu of a specific holding period.

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