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# Behaviour of model pipe piles jacked in calcarenite

## Comportement de pieux tubulaires modèles vérinés dans la calcarénite

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**ABSTRACT**: Evaluation of pile driving feasibility in weak carbonate rocks such as calcarenite requires an estimation of the penetration resistance. Results from an experimental programme are presented during which open-ended model pipe piles were jacked into large intact calcarenite blocks. The failure mechanisms at the pile toe and shaft were characterized. A significant feature of the penetration resistance was its oscillations with trough values as low as 10% of the peak values. Heterogeneity of the block was ruled out as a possible cause of the oscillations after a careful examination. Such behaviour was attributed to repeated calcarenite failures inside the pipe after some incremental penetrations of the pipe. The failure mechanism was confirmed by observing that disk-like fragments were generated inside the pile. At the outer pile-calcarenite interface, a region of crushed material formed. Contributions of pipe shaft and toe annulus to the jacking resistance were evaluated.

**RÉSUMÉ**: Évaluation de la faisabilité du battage de pieux dans des roches carbonatées faibles telles que la calcarénite nécessite une estimation de la résistance à la pénétration. Les résultats d'un programme expérimental sont présentés au cours duquel des pieux modèles à extrémité ouverte ont été introduits par vérinage dans de grands blocs de calcarénite intacts. Les mécanismes de rupture au niveau de la base du pieu et de son fût ont été caractérisés. Une caractéristique significative de la résistance à la pénétration était ses oscillations avec des valeurs de creux aussi basses que 10% des valeurs de crête. L'hétérogénéité du bloc a été exclue comme possible cause des oscillations après un examen attentif. Un tel comportement a été attribué à des ruptures répétées de la calcarénite à l'intérieur du pieu après quelques pénétrations incrémentales du pieu. Le mécanisme de rupture a été confirmé en observant que des fragments en forme de disque étaient générés à l'intérieur du pieu. À l'interface externe pieu-calcarénite, une région de matériau concassé s'est formée. Les contributions du fût du pieu et de l'anneau de la base à la résistance au vérinage ont été évaluées.

**Keywords:** Pile driving; weak rocks; open-ended model pipe piles.

## 1 INTRODUCTION

Recent developments in the domain of renewable energy have led the industry to go offshore on the continental shelf where winds are stronger and steadier for harnessing green energy. One of the challenges in this new environment is the presence of soft carbonate rocks. Pipe piles may have to be driven through hard layers to ensure lateral stability at the design depth. Pile piles must survive the installation process. Wide discrepancies have been reported in the description of cemented carbonate deposits. The term “calcarenite” is often used in the literature to describe cemented carbonate formations (Le Tirant and Nauroy, 1994).

Several studies investigated the shaft and base response of pipe piles in cemented formations through model tests (Jafari et al., 2019; Holeyman, 2017; Montargès, 1988; Settgast, 1980). Results from an experimental programme are presented during which model pipe piles were jacked into calcarenite blocks to investigate jacking resistance and failure mechanisms at the pile toe and shaft.

## 2 SPECIMEN PREPARATION

Model pipe piles were jacked into four calcarenite blocks extracted from Saint-Maximin Quarries in France. The calcarenite is locally referred to as “Roche Douce” or “Roche Saint Leu”. The supplier was Ouachée et Corpechot. Mechanical properties are listed in Table 1. Information regarding microstructure of similar materials can be found elsewhere (Baud et al., 2017; Stavropoulou et al., 2021). It consists of calcite (60%) and quartz (40%) embedded into a calcite matrix and frequent fossils. Each block was an octagonal prism with the diameter of the inscribed cylinder equal to 0.45m, a height of 0.5m, and a mass of about 137kg. Each block was confined with a steel tube of an outer diameter ($D_o$) of 508mm and a wall thickness (t) of 7.9mm. The gap between the calcarenite block and the confining steel tube was filled with non-shrinking grout.

*Table 1. Mechanical properties of the calcarenite (Bosco and Vander Elst, 2018).*

| | Units | Mean (SD*) |
|---|---|---|
| Bulk density | kg/m$^3$ | 1772 (45) |
| Particle density | kg/m$^3$ | 2692 (9) |
| Uniaxial compressive strength ($\sigma_{ci}$) | MPa | 6.8 (1.7) |
| Splitting tensile strength | MPa | 1 (0.2) |
| Elastic modulus | GPa | 7.2 (1.3) |
| Porosity | % | 39 |
| Poisson's ratio | - | 0.22 (0.04) |
| Shear modulus | GPa | 2.9 |

*SD: Standard deviation.

Five jacking tests of model piles with diameter $D_o$ and length L were conducted at various locations as shown in Figure 1c. For tests with shallow penetration depth on one face (face 1), the block was turned upside down and another test was conducted on the intact face (face 2). Information regarding pile geometries, test locations, and the final penetration depth for each test are listed in Table 2.

*Table 2. Description of the model pipes and jacking tests.*

| Model Pile | $D_o$ [mm] | L [mm] | Block | Face | Location | Final depth [mm] |
|---|---|---|---|---|---|---|
| **P4** | 60 | 200 | B | 2 | W | 137 |
| **P5** | 60 | 200 | B | 2 | C | 158 |
| **P6** | 60 | 200 | A | 1 | S | 157 |
| **P8** | 110 | 300 | E | 1 | N | 171 |
| **P9** | 110 | 300 | D | 1 | S | 242 |

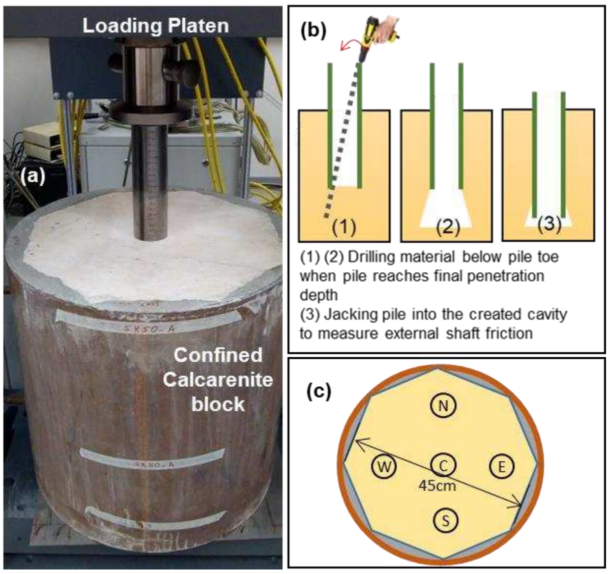

*Figure 1. (a) Typical test configurations for P5 (b) procedure for measuring shaft resistance at the end of the test (c) possible locations on a block for conducting jacking tests.*

## 3 TEST PROCEDURE

In the jacking tests, to avoid development of resistance due to the material accumulating inside the pipe (plug), the pipe was regularly emptied at penetration intervals of about 20mm for the 60mm piles and 35mm for the 110mm piles. Large calcarenite fragments (Figure 2) were recovered by hand or with a drill bit. The remaining fines and smaller fragments were vacuum cleaned from the inside the model piles.

After each pipe had been jacked to the desired depth, a cavity was created at the base of the model piles with a hand drill (Figure 1b). Then the pipe head was further jacked downwards to measure the external friction on pipe wall (Figure 1b). Later, the model pile was filled with non-shrinking grout.

*Figure 2. Disk-like fragments recovered from P4.*

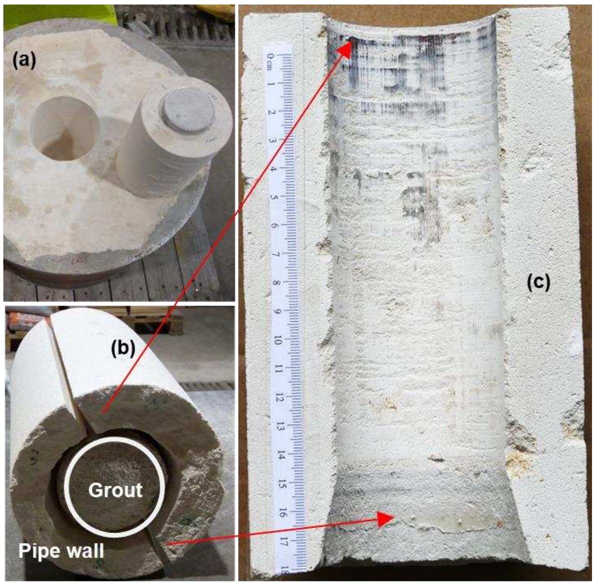

*Figure 3. (a) Model pile (P5) filled with hardened grout cored out of the block (b) core sawn longitudinally to the remove the pipe (c) half of the core showing the pipe-calcarenite interface.*

To analyse the interface of pipe and calcarenite, the pipe and the adjacent calcarenite for P5 was cored out with the aid of a concrete coring bit (Figure 3a). The core was cut longitudinally to detach the pipe from the interface. One half of the core showing the pipe-calcarenite interface can be seen in Figure 3c. The other half was placed inside gypsum to preserve the interface. It was then sawn transversally to see the pipe calcarenite interface as shown in Figure 4. Test setup is shown in Figure 1a. The pile head was axially jacked downwards via strokes of 1mm followed by unloading to below 500N. The velocity was 0.3 mm/min during loading. The force-displacement curve of P4 is shown in Figure 5. The unloading-reloading cycles are removed for visual clarity. Further details on the results and tests can be found in (Jafari, 2021; Jafari et al., 2019).

## 4 RESISTANCE MECHANISM

The force-displacement curves of all model piles exhibited an increasing trend with considerable variations (see e.g., Figure 5). The applied force can decrease down to 10% of the peak values. The Force-displacement curve in Figure 5 exhibits a constant linear part at the end beyond a depth of 137mm. This part is due to the removal of the calcarenite at the pile toe, which leaves only the shaft resisting the pile downward movement. Knowing the shaft skin friction at the end of the test, one can reasonably argue that increasing trend of the applied force is due to the increasing skin resistance with further pile penetration. As the cause of the oscillations, the heterogeneity of the calcarenite was ruled out after a careful examination of the blocks did not reveal any signs of stratification.

Similarly, sudden reductions followed by build-up of the applied forces were reported during penetration of model pipe piles in sand (Paikowsky,1990). This behaviour was attributed to the destruction of arches inside the plug. In our experiments, the plug was regularly removed. The only remaining component of jacking resistance, which can be responsible for the oscillations is the annulus resistance. This is confirmed by the failure mechanism at the pile base.

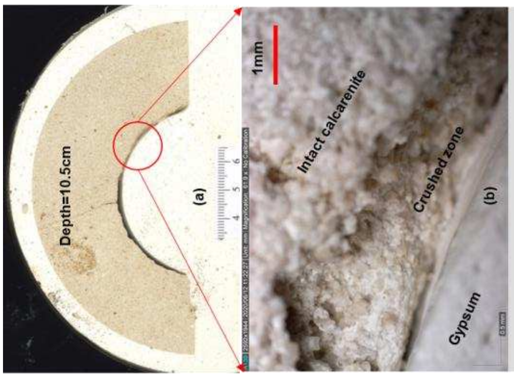

*Figure 4. (a) Transversal cross section of pipe-calcarenite interface for P5 (b) close-up showing crushed region adjacent to external pile wall.*

### 4.1 Failure mechanism at pile base and shaft

During the tests, it was observed that pile penetration into the calcarenite block generated disk-like calcarenite fragments popping up inside the pipe. Figure 2 shows the fragments recovered for P4. The jacking resistance decreased significantly upon formation of a disk-like fragment inside the pipe. Jafari et al. (2019) reported similar Behaviour. This process will be hereafter referred to as “chipping”. The annulus resistance depended on the “chipping type” at the pile toe. In general, the chipping type was either “full chipping” (Figure 2d) or “partial chipping” (Figure 2abc). In full chipping, a full disk-like calcarenite fragment is created inside the pipe after a peak is reached. The penetration resistance was highest prior to full chipping.

Failure patterns at the external shaft of model piles can be seen in Figure 4. A crushed compressed zone was seen to form around the pipe wall as seen in transversal cross-sections (Figure 4). The thickness of the crushed zone is almost equal to the pipe wall thickness. With help of an air blow gun, some of the crushed material could be blown away so that the extent of the crushed zone could be assessed.

The chipping mechanism can be expected to influence the thickness of the crushed zone around the model pile (Figure 4). The pipe penetration results in the volumetric compression of the calcarenite at the pipe tip. The compressed region consists of compacted finely crushed calcarenite forming a doughnut-shape. Intuitively, it could be expected that the radius of the circular cross section of this doughnut increases with penetration depth until some critical embedment $d_{crit}$ is reached. At that point, chipping occurs allowing the pipe to cut through the doughnut and to leave a region of dense fine material at the external and internal faces of the pipe. This process repeats itself with further penetration. The compacted crushed region has a maximum thickness (hence maximum normal stress) at a depth when chipping occurs. At that depth, the calcarenite tends to stick to pipe (leaving a dent on calcarenite interface) when one separates the pipe and calcarenite as seen in Figure 3c.

## 4.2 Periodicity of oscillations in jacking resistance

To understand the frequency content each resistance curve ($F_0$) was decomposed as follows:

1. $F_0$ was de-trended by fitting a fifth order polynomial to find $F_{detrended}$ (Figure 6a)
2. Low frequency content ($F_{smooth}$) is obtained by smoothing $F_{detrended}$ with a moving average filter (Figure 6b).
3. High frequency oscillations ($F_{oscill}$) were obtained as $F_{oscill}=F_{detrended} - F_{smooth}$ (Figure 6b)
4. Scalograms of both high and low frequency contents were constructed (Figure 6b-c).

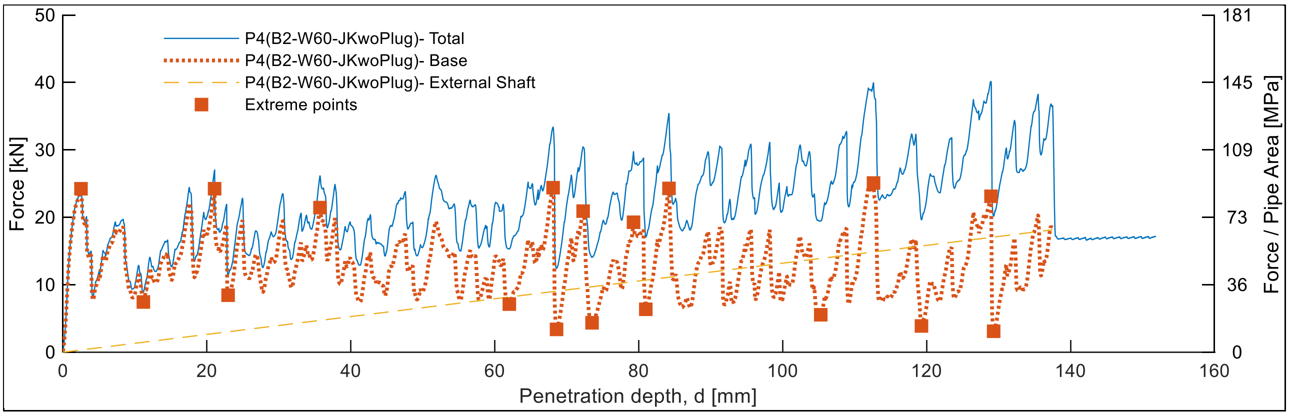

*Figure 5. Typical force-displacement curves for test P4 with the estimated shaft and annulus components.*

The peaks in the $F_{smooth}$ curve corresponded to when full chipping occurred in the tests. On the other hand, the peaks in the $F_{oscill}$ corresponded to when partial chipping occurred.

From the scalograms, it was found out that on average:

- The high frequency component has a period of 4mm for the 60mm-piles while it has a period of 8mm for the 110mm-piles. These periods are about $0.07D_o$.
- The low frequency content has a period of 12mm for the 60mm-piles while it has a period of 27mm for the 110mm-piles. These periods are about $0.23D_o$.

The period of the low and high frequency components of the signals from 110mm-piles is about two times that of the 60mm-piles. These results indicate that the resistance oscillations depend on the pile diameter rather than the pile wall thickness in contrast to what was reported by Jafari et al. (2019).

## 4.3 Shaft resistance

External shaft resistance at the end of the tests was measured by jacking the pipe into a cavity created below the pipe tip (Section 4). Assuming a linear increase of shaft resistance with penetration depth (Figure 5), one can compute an average shear stress $\tau_{ave}$ on the pipe outside wall. $\tau_{ave}$ is 440 kPa and 405 kPa for the 60mm and 110mm piles, respectively. These values are about 6% of $\sigma_{ci}$.

These values are consistent with laboratory experiments by ARGEMA (Association de Recherche en GEotechnique MArine) in which small piles were *driven* in limestone with 5MPa< $\sigma_{ci}$ <25MPa. Skin friction values were between 7 to 9 percent of $\sigma_{ci}$. In addition, pullout tests of driven piles in cemented carbonate formations exhibited skin friction values reaching 300 kPa in formations with $\sigma_{ci}$ ranging from 3.5 to 5MPa according to Le Tirant and Nauroy (1994). High shaft friction values seem to be typical of model pipe piles installed in carbonate rocks. These results may be used combined with the investigation of rock-steel interfaces after Ziogos et al. (2023) to better understand the skin friction of crushed calcarenite and the model steel pipe pile.

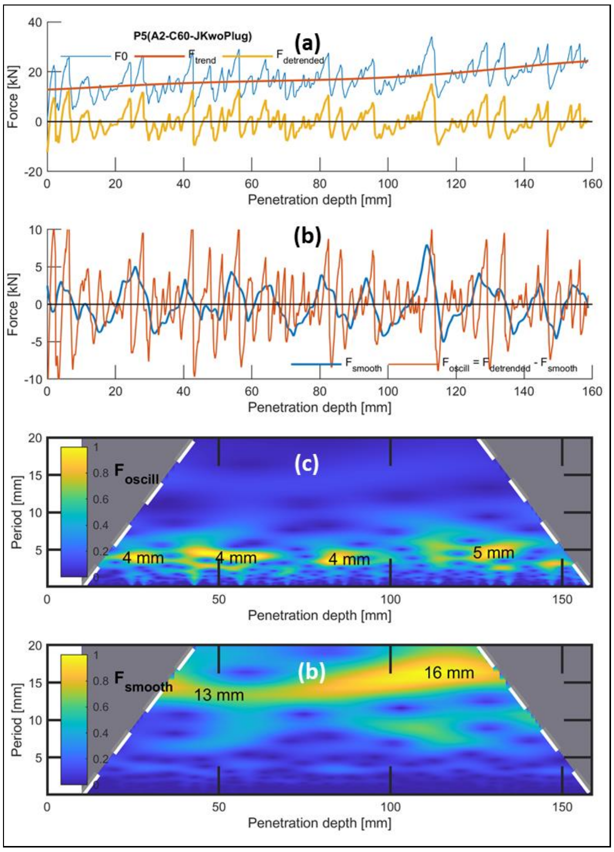

*Figure 6. (a) De-trending of penetration resistance for P5 (b) decomposition of detrended curve into high frequency and low frequency curves (c) (d) scalograms of Foscill and Fsmooth.*

## 4.4 Annulus resistance

By subtracting the shaft resistance from the total jacking resistance, one can obtain the annulus resistance. The estimated annulus resistance falls in a band of peak and residual values (Figure 5). For the peaks with the highest prominence, full chipping occurred (Section 4.1). The *findpeaks* function of Matlab® was used to identify all the peaks and troughs of a curve with a prominence equal to 30% of the maximum annulus resistance. This criterion proved relatively effective in capturing the peaks and troughs associated with full chipping as seen in Figure 5. Mean peak annulus stress of all the model piles is 85MPa = 12.5$\sigma_{ci}$ while mean residual annulus stress is 23MPa = 3.4$\sigma_{ci}$. No discernible scale effects were observed between the annulus capacity of the 60mm and 110mm model piles. The estimated residual annulus stress is close to upper bound suggestion by Le Tirant and Nauroy (1994), which is the minimum of 4.5$\sigma_{ci}$ and 12 MPa. The authors (Jafari, 2021; Jafari et al., 2019) investigated numerically the bearing capacity of open-ended pipe piles in intact rock. The annulus bearing capacity did not depend on the $D_o/t$ for the common ranges in practice ($D_o/t$ < 100). With increasing embedment depth, a maximum annulus capacity $q_b$ was approached. A fit to those numerical results leads to an annulus bearing capacity of 11.8$\sigma_{ci}$. This value is in good agreement with the mean peak stress of the jacked model pile which is 12.5$\sigma_{ci}$. Prediction of the residual bearing capacity in terms of the intrinsic properties of the medium is an area open to further research.

## 5 CONCLUSIONS

Model pipe piles were jacked into relatively large blocks of a reference calcarenite. The model piles were jacked down to 1.5 to 2.5 times pipe diameter. Penetration resistance was measured. During jacking, the material accumulating inside the pipe was removed at regular intervals. The total jacking resistance was split into annulus and shaft resistance components. Annulus resistance exhibited important oscillations, which was attributed to calcarenite chipping mechanisms inside the pipe. The period of the oscillations depended on the pile diameter rather than pile wall thickness. At the pile-calcarenite interface, a region of compacted crushed material formed over a thickness of the order of that of the pipe wall.

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