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Plug monitoring during vibratory monopile driving in centrifuge testing

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ABSTRACT: Monopiles are a common foundation type for offshore wind turbines. Compared with the impact driving method, vibratory installation is a potential alternative to improve the installation speed and reduce noise emissions. Plug development affects the soil resistance during driving (SRD) and the in-service capacity after monopile installation. However, studies on plug development in vibratory piling are limited compared to impact driving and jacking, which may hinder the application of purely vibration based installation. The driving properties and soil response of the vibration installation method are distinct from other methods and current understanding of plug evolution may not be applicable. This paper presents the setup of a centrifuge vibratory driving and monitoring system and outlines the preliminary results of a centrifuge model test investigating the plug development. A centrifuge model test was performed to drive an instrumented model pile in a dry medium-dense sand bed. Partial plugging was observed during the vibratory penetration, and the incremental filling ratio (IFR) showed that the partial plug was formed at the rapid installation stage of the driving. Further equipment development and testing will be undertaken based upon these preliminary findings.

1 INTRODUCTION

Monopiles are the most commonly used foundation type for offshore wind turbines in shallow water (Bienen et al., 2023). The conventional impact-driving method, where hammer blows are employed at the pile top, may cause problems with noise emissions and steel fatigue damage. Jacking methods have also been attempted for offshore piles (Davidson et al., 2024), but these techniques require further development (Igoe et al., 2013).

Vibratory driving is a potential alternative for offshore foundations with lower noise (Molenkamp et al., 2024) and faster installation. Growing research interest has been directed toward the vibratory method, encompassing field test campaigns and both physical and numerical modelling of the piling process and load capacity developed (Esfeh et al., 2026; Fang et al., 2025; Hein Mazutti et al., 2026; Martinelli et al., 2025; Spill & Lillie, 2025; Tsetas et al., 2023).

However, limited studies appear to focus on the plug behaviour during vibratory pile penetration, which affects the soil resistance during driving (SRD) and the in-service capacity after installation. During vibratory driving, high frequency driving force up to and exceeding 20 Hz is applied to the pile system and this dynamic process may cause different soil behaviour and plug development compared to the impact and jacking methods (Martinelli et al., 2025; Tsetas et al., 2023). Partially plugged driving has been observed in numerical simulations. A clear partial plug was shown in Fang et al. (2025) after an open-ended pile was vibro installed into medium-dense sand in 3D Discrete element method (DEM) simulation. Li et al. (2021) reported incremental filling ratio (IFR) values that reduced with vibratory penetration depth and reached around 0.6 at the final stage in loose sand in a 2D DEM simulation. Similar results have also been obtained from the Finite element method (FEM) simulations. Esfeh et al. (2026) conducted a series of vibratory pile driving simulations using FEM methods and partial plug were observed in medium-dense and dense sand at the installation frequency of 23 Hz.

Only limited studies have concentrated on plug development in vibratory penetration with comparison to impact driving or jacked installation, although the plug influences the installation and capacity (Cerfontaine et al., 2023; Zheng et al., 2025). It is therefore important to investigate the plug behaviour to further understand the influence of vibration on the plug development during vibratory pile driving and provide support for vibratory driving resistance assessment and in-service capacity analysis. Results from numerical simulation may differ with different model selection and parameter settings and field tests may be extremely expensive and time-consuming to undertake. Compared to the numerical simulation and field tests, physical modelling offers a cost and time effective option with controlled and repeatable conditions.

To this end, a vibration hammer for pile installation in a centrifuge environment was designed and fabricated, the pile was instrumented with an accelerometer, displacement sensor for pile movement, and strain gauges to record the pile behaviour during vibratory penetration. A unique plug (Davidson et al., 2024) monitoring system was employed to measure the plug development during vibratory piling. A preliminary 10g centrifuge model test was performed to drive an instrumented model pile in dry medium-dense sand bed. This paper is intended to detail the vibratory actuator and instrumentation development and presents the preliminary results of the penetration response and the plug monitoring. The plug length was recorded during the whole vibratory piling process. The result can then be used to calibrate and verify planned numerical simulation, and the setup will be applied for the future centrifuge tests.

2 CENTRIFUGE TESTING METHODOLOGY

Centrifuge modelling was adopted to investigate the plug development during vibratory piling. This section details development of the vibration hammer, instrumentation of the pile and data acquisition (DAQ) systems.

2.1 Vibration hammer design

Driving frequency is a significant parameter in vibratory installation and interacts with other factors that affect the driving performance (Fang et al., 2024). Based on the scaling rules in centrifuge tests, the vibratory frequency is N times the prototype value, where N is the g level in the centrifuge tests.

To achieve similitude, a vibratory hammer that can vibrate at high frequency is needed. A conceptual design using an undulating wheel and a vertical slider was proposed by Mazutti et al. (2024). The working principle is that the power from the motor is transmitted by a belt and pulley system and drives an undulating wheel. A vertical slider is guided by the wheel where the motion frequency is amplified by the number of the undulations on the wheel surface.

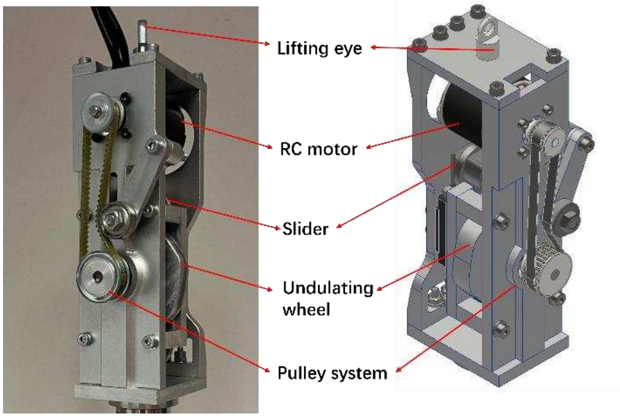

Figure 1. Overview of the vibration hammer for centrifuge tests.

In this research, the original concept of undulating wheel (Mazutti et al., 2024) was adopted and updated to be compatible with the current centrifuge system at the University of Dundee, as shown in Figure 1. The number of undulations on the wheel was 7 and two bearings mounted at either end of a slider that followed the shape of the wheel, exciting the slider and generating the cyclic driving force. A lifting eye at the top of the hammer was designed for crane-controlled installation and tensile tests. The model scale properties of the vibration hammer are shown in Table 1.

Table 1. Properties of the vibration hammer.

Vibro-hammer properties	Value
Mass, m_{vh} [kg]	1.18
Maximum frequency, f_{max} [Hz]	310
Eccentric moment, M_e [$g \cdot mm$]	164.26
Maximum dynamic force, f_d [N]	289.76

2.2 Instrumentation and DAQ system

The aim of the test programme was to conduct vibratory pile installation, measure the driving force and acceleration during piling and continuously monitoring the pile displacement and the behaviour of the internal pile plugging.

Figure 2 shows the pile instrumentation. An aluminium cylinder ((2) in Figure 2) was employed to connect the vibration hammer and the pile. A plastic shaft collar ((4) in Figure 2) was fixed to the model pile to mount the pile accelerometer and the external displacement sensor. A pair of strain gauges ((7) in Figure 2) with Kapton type protection was attached to the pile to measure the axial force at the top of the pile. A 3D printed holder ((3) in Figure 2) was mounted inside the pile wall for the sensor mounting and to measuring the internal plug.

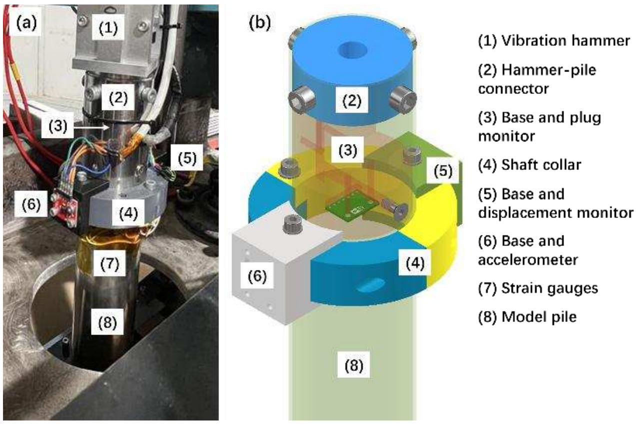

Figure 2. Detail of the instrumentation of the model pile.

The acceleration during the vibratory driving was recorded by SparkfunADXL377 (± 200 g) analogue accelerometer. It was powered by a 3.3 V supply. The strain gauges used were FCB-6-350-11-F (350 Ω resistance) and they were powered by a 10 V supply.

Davidson et al. (2024) previously developed a plug monitoring system for centrifuge push-in piling. A digital laser displacement sensor with a signal booster next to it was mounted inside the pile to measure the plug development. The digital signal was received by an Arduino and then transmitted to the centrifuge on-board CompactRIO (cRIO) DAQ. A similar setup was employed in this study. Plug development ((3) in Figure 2) and pile displacement ((5) in Figure 2) were monitored by the same Time of Flight (ToF) laser VL53L1X sensors from ST Microelectronics, which were mounted on a Pololu development board. The displacement sensor provides a resolution of 1 mm, with a measurement range extending up to 4 m. To simplify the measurement system, the digital signal from VL53L1X sensors were amplified by one booster, signals from plug measurement sensor ((3) in Figure 2) and pile displacement sensor ((5)) were transmitted to an Adafruit LTC4311 I_2C extender and sent to an Arduino Uno R4. The booster and the Arduino were encapsulated in a 3D printed enclosure to prevent noise, as shown in Figure 3. Sensor operation and data acquisition were implemented by Arduino software and then the serial output from the Arduino was transferred to the cRIO.

All the signals from various sensors were integrated into cRIO DAQ system. The sampling frequency was set at 3571 Hz. The maximum frequency of the vibration hammer is 310 Hz, the rate of the sampling and vibration frequency is 11.52, which is greater than the theoretical minimum value (Nyquist rate) of 2. In the DAQ system, accelerometer, strain gauges, and load cell can record data at 3571 Hz, but the displacement sensors for pile movement and plug behaviour monitoring sample data at 10 Hz due to the limitation of the VL53L1X sensor.

2.3 Test setup

The test setup is shown in Figure 3. The screw pile installation actuator (Wang et al., 2025) at the University of Dundee was modified to fit the vibratory piling system. A 3D printed enclosure to prevent the signal noise was used as a base for the signal booster system, which amplified the signal from the pile displacement and plug sensor. A miniature in-line load cell DDE-5000N was mounted on the actuator beam and was connected to the vibration hammer. This load cell can be used for the tensile capacity test after the installation and the planned cable-controlled pile installation. A 3D printed guide was mounted on the rig to ensure axial alignment of the pile during installation.

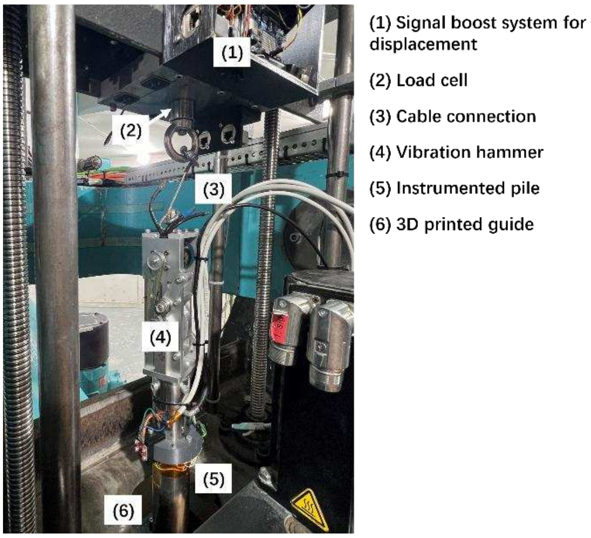

Figure 3. Test setup for vibratory installation.

2.4 Sand bed properties and model pile

A medium-dense soil bed ($D_r \approx 54\%$) with 434 mm depth was adopted in this study, which was prepared by dry slot air-pluviation method in a 500 mm × 800 mm × 550 mm strong box. HST95 sand was used where the properties have been fully investigated in previous studies in the University of Dundee, as shown in Table 2.

A 500 mm long stainless steel pile with 50.8 mm outer diameter (D_{out}) and 47.8 mm internal diameter (D_{in}) was employed for the test. An aluminium cylinder connected the pile and vibration hammer rigidly. The ratio of D_{out}/D_{50} was 362.85, which is above the recommended minimum ratio of 50 for a model pile (Fioravante, 2002; Garnier et al., 2007). The wall thickness of the pile installed was 1.5 mm at model scale, and the ratio t/D_{50} was 10.71. This ratio is line with the values in published results from centrifuge tests ranging from 2.7 to 17 (Fan et al., 2021; Henke & Bienen, 2014). The diameter-to-thickness ratio of the model pile was 33.87.

Table 2. HST95 sand properties (Al-Defae et al., 2013; Lauder, 2010)

Properties	Value
Effective particle size, $\boldsymbol{D_{10}}$ [mm]	0.09
Average particle size, $\boldsymbol{D_{50}}$ [mm]	0.14
Critical state friction angle, $\boldsymbol{\phi'_{crit}}$ [°]	32
Peak friction angle, $\boldsymbol{\phi'_{pk}}$, medium-dense [°]	41
Angle of dilation, $\boldsymbol{\psi}$, medium-dense [°]	11.2
Maximum dry density, $\boldsymbol{\rho_{max}}$ [$\boldsymbol{kN/m^3}$]	17.58
Minimum dry density, $\boldsymbol{\rho_{min}}$ [$\boldsymbol{kN/m^3}$]	14.59

** From peak strength relationship from direct shear tests for data at effective stresses between 50 and 200 kPa, at 80% relative density.*

2.5 Testing programme

The pile was freely driven under vibration into medium-dense dry sand. An overview of the test at prototype scale is shown in Table 3. The test was conducted at 10g. The total mass of the test system including vibration hammer, model pile and instrumentation M_{tot} was 2260 kg (2.26 kg at model scale), which induces the static force F_s of 22.148 kN (221.48 N at model scale). The vibration frequency for pile driving was 21.14 Hz in prototype. The ratio of the dynamic force and static force F_{dyn}/F_s was 1.31, which exceeds the limitation of vibratory installation of F_{dyn}/F_s =1 (Hein Mazutti et al., 2024). The refusal of installation was defined here as an advancement rate of 1 cm/min at prototype scale (Holeyman et al., 2020), which was also adopted at Hein Mazutti et al. (2026). The total installation time was 12.59 minutes at prototype scale, and the total number of vibration cycles applied was 15974.

Table 3. Overview of the test (prototype scale)

Properties	Value
g-level	10
Mass of the test system, $\boldsymbol{M_{tot}}$ [kg]	2260
Static force, $\boldsymbol{F_s}$ [kN]	22.15
Driving frequency, $\boldsymbol{f}$ [Hz]	21.14
Dynamic force, $\boldsymbol{F_{dyn}}$ [kN]	28.98
Ratio of dynamic to static force, $\boldsymbol{F_{dyn}/F_s}$ [-]	1.31
Final installation time, $\boldsymbol{t_{tot}}$ [min]	12.59
Final cycle numbers, $\boldsymbol{n_{cycle}}$ [-]	15974

3 RESULTS AND DISCUSSION

3.1 Penetration response

The pile installation progress is shown in Figure 4. The initial penetration due to the self-weight of the test system was approximately 0.1 m ($z/D \approx 0.197$), the vibratory driving started at this point. The ultimate penetration depth was 1.14 m ($z/D \approx 2.24$). Rapid penetration can be observed up to approximately 0.9 m penetration ($z/D \approx 1.77$) but then the pile slowed down gradually with increasing depth.

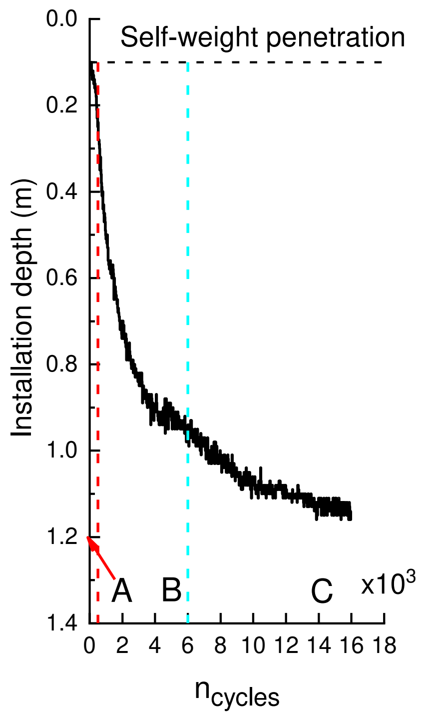

Figure 4. Summary of installation progress and number of vibratory cycles applied.

Acceleration recorded during the vibratory installation is shown in Figure 5 (a). It should be noted that the accelerations presented in Figure 5 are the peak values of the downward penetration cycles. The whole process can be divided into 3 stages. In the first stage (Stage A shown in Figure 5 (b)), the vibration piling started and a sharp increase in penetration can be observed. The acceleration increased from 0 to 1.6 g within 400 cycles (1.89 s at model scale and 0.39 mins at prototype scale). This result comes from the reaction time of the motor and power transmission system shown in Figure 1. A gradual drop of the downward acceleration from 1.6 g to 1.1 g was shown after the peak (Stage B in Figure 5). This observation is different from the results reported in Hein Mazutti et al. (2026), where no obvious decrease of the acceleration was shown.

One possible explanation is that the pile wall thickness in this study is 1.5 mm (model scale), which is 3 times that (0.5 mm in model scale) employed in Hein Mazutti et al. (2026). Constant driving force and static force (self-weight of the system) after the vibration fully started (at the end of stage A in Figure 5(a)). A more significant tip resistance was developed and the total force decreased, which lead to a decrease in the acceleration. At the start of stage B, the pile maintained a relatively large acceleration which led to a rapid advance of the pile, as shown in Figure 4. At stage C, the downward acceleration essentially remained at 1 g, and the pile penetration slowed down (Figure 4), which is similar to the observation from Hein Mazutti et al. (2026).

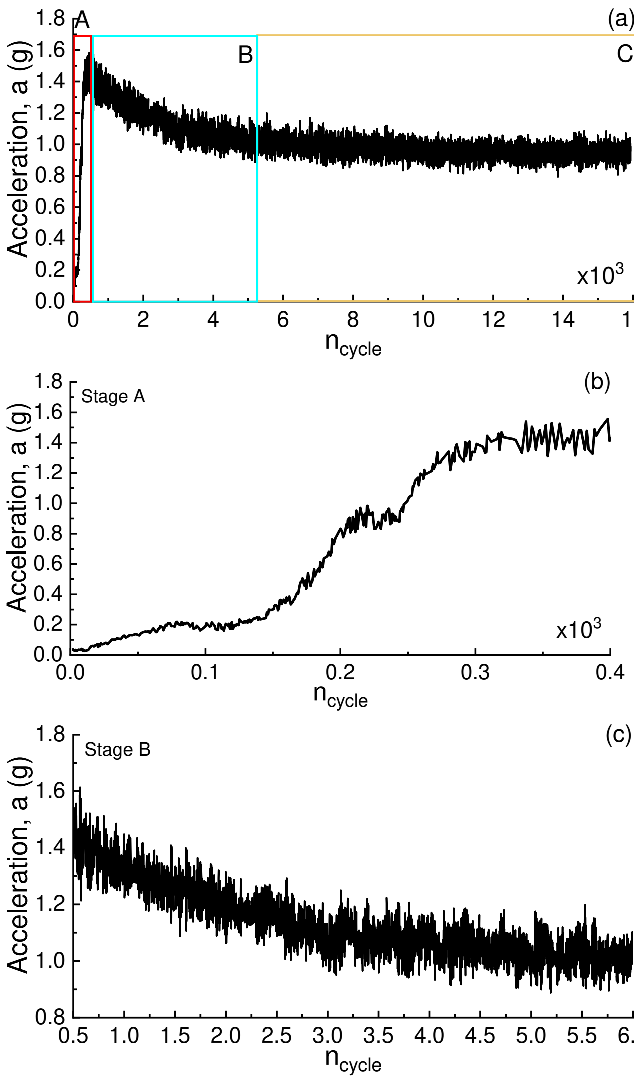

Figure 5. Summary of Acceleration during vibratory installation: (a) overall process; (b) stage A; (c) stage B.

3.2 Plug monitoring

Figure 6 shows the plug development during the vibratory driving. It can be observed that a partial plug occurs during the installation. This result is in line with the DEM simulation results presented by Fang et al. (2025), a partial plug was observed after a vibratory installation at 21.5 Hz in medium-dense sand (outer diameter D = 1 m, the refusal depth was $4.2D$). Similar observations were also reported in FEM simulations. Partial plugging was observed after an 8 m diameter pile vibratory penetrated (23 Hz) to $3.125D$ at D_r = 50% in FEM modelling (Esfeh et al., 2026).

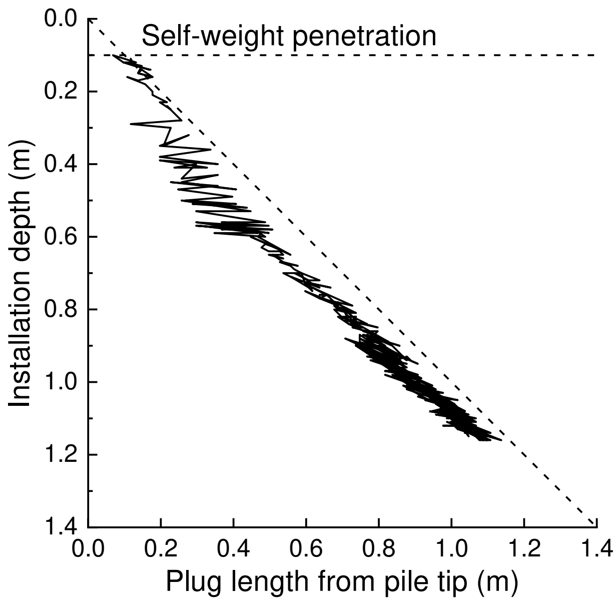

Figure 6. Plug length (measured from pile tip) development during vibratory installation.

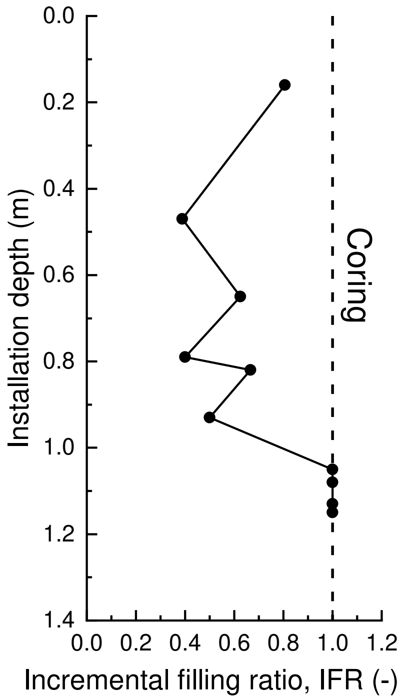

Figure 7. Incremental filling ratio (IFR) during the vibratory installation.

After the vibration starts, the height of the sand inside the pile shows a slower rate of increase compared to the pile penetration until the pile penetration depth of approximately 0.9 m ($z/D \approx 1.77$). It can also be noticed from the incremental filling ratio (IFR) in Figure 7, that the values are less than 1, the pile is partially plugging at this stage. From this point to the pile refusal depth at 1.14m ($z/D \approx 2.24$), the plug length increases in line with the pile displacement. IFR = 1 can be observed from Figure 7, the pile presents unplugged (coring) penetration.

The plug observation is different from the plug development in driven or jacked piles. IFR values in these installations were observed reducing from 1 to smaller values, coring occurred at the beginning of the penetration and the pile plugged with further advancement (Davidson et al., 2024; Ko & Jeong, 2015).

4 CONCLUSIONS

In this research, a vibration installation device was fabricated for the pile installation, and the pile was instrumented with sensors to record the pile behaviour during vibratory driving. A unique plug monitoring system was employed to measure the plug development during vibratory piling. A 10 g centrifuge model test was conducted to drive the instrumented model pile in dry medium-dense sand bed. The pile was vibrated installed at 21.14 Hz to the ultimate refusal depth at 1.14 m ($z/D \approx 2.24$). Pile acceleration was recorded and a gradual decrease was observed after the peak at the beginning of penetration. Partial plugging was observed during the vibratory penetration. The IFR results show that the partial plug was formed at the rapid penetration stage. At the final stage of the vibratory driving, the pile presents unplugged (coring) penetration. This study represents preliminary testing and development of a centrifuge-based model pile installation system. Further development and testing will be undertaken based upon these preliminary findings.

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