Instrumented Pile Load Testing Using Vibrating Wire Strain Gauges with Supporting Low-Strain Integrity Assessment in Transmission Line

Rizwan Tariq, SMIEEE
Department of Electrical Engineering
National Power Construction Corporation Limited
Saudi Arabia
engr.rizwan101@gmail.com

Krishna Kumar Krishnamoorthy
Department of Civil Engineering
National Power Construction Corporation Limited
Saudi Arabia
msk.krishnakumar@gmail.com

Ibrahim Ali AlMohaisin
Association of Electrical Engineering & Energy (AEEE)
Riyadh, Saudi Arabia
iamohaisin@ieee.org

Awais Afzal
Department of Electrical Engineering
National Power Construction Corporation Limited
Saudi Arabia
engr.awaisafzal@gmail.com

***Abstract*— The present paper examines the cast-in-situ pile foundations that support transmission line towers through instrumented static load testing and low-strain pile integrity testing. A pile with a diameter of 1.00 m and a length of 17.75 m was subjected to axial loading of up to 2.00 times the working load (2029.62 kN). At five different depths, vibrating wire embedment strain gauges were utilized to measure the distribution of axial load and the mobilization of shaft friction. The maximum observed settlement at the pile head was 3.51 mm. Analysis of load transfer revealed that significant skin friction mobilization occurred at depths ranging from -7.77 m to -9.47 m below the Existing Ground Level (EGL). Low-strain integrity testing confirmed that two piles of a tower foundation were continuous, with no significant anomalies detected, while suspected major anomalies were observed in the other two piles. These findings illustrate the effectiveness of using combined strain-gauged load testing alongside integrity testing for the assessment of pile foundations.**

Keywords*— *Strain Integrity Test, Vibrating Wire, Stress impulse, Strain Gages, Pulse Echo Method, Continuity, Velocity

I. INTRODUCTION

Instrumented Pile Load Test using Vibrating Wire Stain Gauge and Strain Pile Integrity Test on Pile Foundations for Transmission Line Towers are crucial for ensuring the load distribution along the pile shaft, structural integrity and reliability of the tower pile foundation. Such tests provide valuable insights into the structural condition of the piles and help identify any potential defects or weaknesses. By implementing these assessments, we can enhance safety, extend the lifespan of the pile foundation, and minimize the risk of costly failures. This proactive approach ultimately contributes to the overall efficiency and stability of the electrical transmission network.

II. KEY TESTS FOR EVALUATING PILE FOUNDATIONS

The growing demand for construction on challenging landscapes has increased the use of piles for supporting buildings and infrastructure, especially in transmission line foundations. This has led to a need for tests to evaluate pile load capacities, responses under load, necessary pile lengths, and to identify geometric issues like necking, cracking, and voids, as well as assess concrete quality in both test and working piles.

Various type of tests are available to evaluate the condition of pile foundations; however, the following two methods are the major ones followed across the construction field.

- Instrumented Pile Load Test using Strain Gauges
- Low Strain Pile Integrity Test

A. Instrumented Pile Load Test using Strain Gauges

In 1931, a French Consulting Engineer developed a process for measuring strains using the vibrating wire principle as in [1]. During the same decade, Maihak in Germany and Telemac in France commercially introduced vibrating wire strain gauges. Innovations from the Buildings Research Establishment in England and the Norwegian Geotechnical Institute also influenced designs. Since the 1970s, Geokon Inc. in the USA has expanded the variety and versatility of vibrating-wire sensors. Figure 1 shows a typical vibrating wire concrete embedment strain gage.

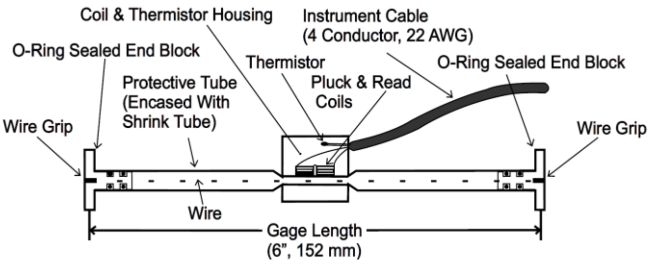

Fig. 1. Vibrating Wire Embedment Strain Gage

A tensioned steel wire is set into vibration using an electronic coil. This coil, together with a permanent magnet, can also detect the frequency of this vibration, which varies as the wire experiences strain. The style of concrete embedment features flanges at both ends to connect with the concrete as in [2].

In static load testing, vibrating wire strain gauges are preferred due to their frequency-based output, which enables long-distance transmission and remains unaffected by

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corrosion, moisture, or temperature changes. Unlike electrical resistance sensors, changes in cable length do not impact the frequency signal. Portable devices and smaller, more efficient dataloggers have facilitated their increased use in projects like pile tests, allowing for quick data collection and simplified analysis as in [3]. Figure 2 shows a typical datalogger.

Fig. 2. Datalogger

This test to be conducted on the non-working pile along with the pile uplift test in order to obtain the information about Load distribution, Skin friction along the pile shaft and Pile settlement behavior in prior to commence the construction of pile foundation.

Procedure

The 380 kV overhead transmission line runs between the SWPC 3B Substation and Jubail Residential BSP in the Kingdom of Saudi Arabia. This transmission line is approximately 60 kilometers long and consists of 167 towers, all of which are built on pile foundations. Among them, the two types of towers are tested for the Strain Integrity Test, along with the Pile Uplift Test. However, for the study purpose, we will examine in this article only about Tower Type – F-T2. The subsurface profile of the pile consisted of fill underlain by poorly graded sand with loose gravel up to 7.50 m, followed by denser soil extending to 9.00 m, and elastic clayey silt intermixed with cemented bands to the pile toe level. Groundwater was encountered at a depth of approximately 0.55 m below ground level.

TABLE I. PILE FOUNDATION DETAILS

Tower Type	**Pile Dimensions**		**Pile Load**	
	Diameter, m	***Length, m***	***Working Load, kN***	***Test Load, kN***
F-T2	1.00	17.75	1014.81	2029.62

Installation of Vibrating Wire Strain Gage

Each gauge must have a unique identifying code (in addition to the serial number) for its specific position within a pile, with longer cables marked for remote installations. Ensure cable length is adequate to reach the designated readout site. The height or position of the Strain Gauge installations should be specified by the Engineer responsible for data analysis or indicated in the contract documents. Additionally, gauges must be protected from damage due to their sensitivity as referenced in [4].

Before attaching the gauge, it was linked to the Vibrating Wire Readout device to verify that it was functioning properly. The readout's "Audio" function was utilized to ensure that the gauge delivers a consistent and clear signal. In this test, the strain gauges were set up at five different levels, with three gauges allocated to each level. The strain gauges were positioned in the pile foundation at specified levels i.e. +1.23m, -0.27m, -7.77m, -9.47m, -15.22m from Existing Ground Level, EGL.

Embedment strain gauges are secured to mounting bars within the concrete structure's reinforcement cage, providing stable support during concrete placement. The gauge tubes are protected by polyolefin sleeves. Wrap the mounting bar with six to eight turns of PVC or paper tape for proper grip. Choose gauges with cable lengths that avoid splicing inside the pile; if needed, use waterproof materials for connections and mark cable ends with a unique color code. Position and secure the mounting bars with steel tying wire, and attach the gauge using nylon cable ties, ensuring it's aligned with the main bars. Figure 3 shows an installed strain gauge. Guide the cable alongside the main bar to minimize damage risk and protect it during installation to prevent concrete exposure. Then, shield the cables after completing the pile cap of the pile foundation.

Fig. 3. Installed Strain Gauge on Pile Steel Cage

Once the pile foundation has attained its strength, an uplift test setup will be installed in accordance with ASTM D3689-07, which outlines the standard test methods for deep foundations subjected to static axial tensile loads as in [5]. This setup will apply an external uplift force to the foundation through an embedded steel angle member. In prior to starting the uplift test on the pile foundation, the strain test cables must be connected to the data logger.

Initial readings of strain gauges were recorded before the axial load test. After completing necessary checks, the Instrumented axial tensile load test was performed using a Kentledge Beam and hydraulic pistons. Pile head displacement was measured with four dial gauges and displacement transducers, while live strain gauge data was displayed via data loggers. The recorded data was imported into a spreadsheet to plot moment distribution along the pile, allowing analysis of its behavior under load and calculation of skin friction and load transfer to the pile shaft. The strain sensors were monitored during the course of pile load test at zero loads and for each loading cycle. The readings were taken for 10%, 50%, 100%, 150%, & 200% of the working loads for both loading and unloading stages.

To compute Pile Load Transfer Characteristic

For all strain gauges, the strain, "µ Strain" shall be computed as follows,

$$\mu \text{ Strain} = (\text{Gauge Factor}) \times (F_1^2 - F_0^2)/1000 \tag{1}$$

where, F0 & F1 in Equation (1) are Initial and subsequent Hz readings, Gauge Factor is 3.204.

To calculate the Load on Concrete and Steel as in [5],

$$\text{Load on Concrete} = (\mu \text{ Strain})^{-6} \times Ec \times (Ap\text{-}As) \tag{2}$$

$$\text{Load on Steel} = (\mu \text{ Strain})^{-6} \times Es \times As \tag{3}$$

$$\text{Total Load} = \text{Load on Concrete} + \text{Load on Steel} \tag{4}$$

where, Ec is Elastic Modulus of Concrete
Es is Elastic Modulus of Steel

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Ap is Area of Pipe Foundation

As is Area of Steel

The total load is calculated using the obtained data from strain gauges installed at various levels and during different loading stages are tabulated below,

TABLE II. TOTAL LOAD AT DIFFERENT LEVELS

Load Stage[a], kN	Level, m (from EGL)[b]				
	+1.23	-0.27	-7.77	-9.47	-15.22
	Calculated Total Load[a] at different levels, kN				
-101.48	-93.20	-87.00	-45.90	-15.30	-2.70
-507.41	-478.20	-431.80	-312.30	-85.20	-21.90
-1014.81	-975.50	-896.80	-674.70	-155.50	-35.00
-1522.22	-1474.30	-1362.30	-1045.30	-322.70	-53.30
-2029.62	-1988.40	-1840.70	-1424.40	-385.60	-70.00

[a] Negative sign (-) in load denotes an incremental load

[b] Positive sign (+) in level denotes the elevation above Existing Ground Level, EGL, while negative sign (-) in level denotes the elevation below Existing Ground Level, EGL

A graph is plotted based on the applied load and the load distribution along pile shaft (Refer Figure 4).

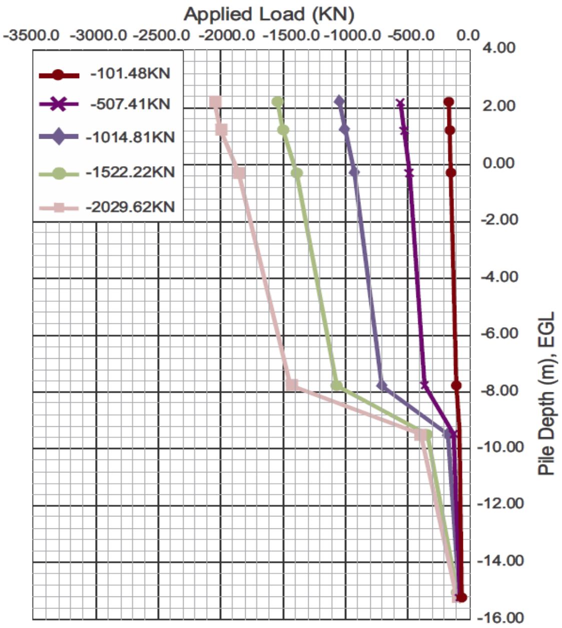

Fig. 4. Applied Load and Load Distribution along Pile Shaft

To compute Pile Friction Behavior

The average unit skin friction of any layer between any two strain gauge sections of the pile can be calculated by the changes in load divided by the circumference area between the two sections, as the following equation,

$$F_s = (P_{z1} - P_{z2}) / (\pi D (Z_1 - Z_2)) \quad (5)$$

where,

F_s is Average shaft friction between depth Z_1 and Z_2

P_{z1} is Axial Load at the depth Z_1

P_{z2} is Axial Load at the depth Z_2

Z_1 is Depth at z_1

Z_2 is Depth at z_2

D is Pile diameter at this section

The unit skin friction along pile shaft is calculated using the obtained data from strain gauges installed at various levels and during different loading stages are tabulated below,

TABLE III. UNIT SKIN FRICTION AT DIFFERENT LEVELS

Load Stage[a], kN	Load (%)	Strain Gauge Levels (from EGL)[b]			
		+1.23 to -0.27	-0.27 to -7.77	-7.77 to -9.47	-9.47 to -15.22
		Unit Skin Friction[c] (kN/m2)			
-101.48	10%	-1.3	-1.7	-5.7	-0.8
-507.41	50%	-9.8	-5.1	-42.5	-3.8
-1014.81	100%	-16.7	-9.4	-97.2	-7.2
-1522.22	150%	-23.8	-13.5	-135.3	-16.2
-2029.62	200%	-31.3	-17.7	-194.6	-19.0

[a] Negative sign (-) in load denotes an incremental load

[b] Positive sign (+) in level denotes the elevation above Existing Ground Level, EGL, while negative sign (-) in level denotes the elevation below Existing Ground Level, EGL

[c] Negative sign (-) in unit skin friction denotes a progressive friction along the pile shaft

A graph is plotted based on the applied load and the unit skin friction along pile shaft (Refer Figure 5).

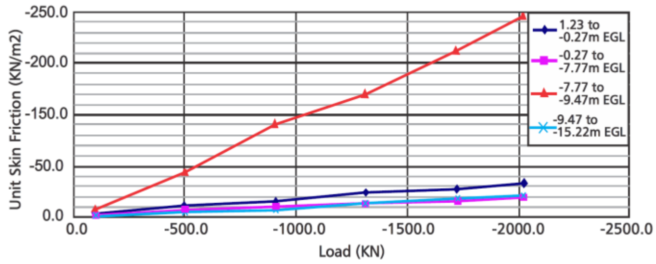

Fig. 5. Applied Load and Unit Skin Friction along Pile Shaft

To compute Pile Head Displacement

The load–uplift displacement response of an axially loaded pile is governed by pile compressibility, pile–soil interface friction mobilization, and the load–displacement behavior of the pile tip soil. The load and movement readings recorded during the loading test are tabulated below,

TABLE IV. LOAD & MOVEMENT AT DIFFERENT LOADING STAGES

Load Stage[a], kN	Pile Readings				Average Gauge Reading	Total Movement[b]
	1	2	3	4		
-101.48	11.68	10.88	12.63	11.14	11.58	0.00
-507.41	12.04	11.27	13.23	11.65	12.05	-0.47
-1014.81	12.67	11.92	13.81	12.25	12.66	-1.08
-1522.22	13.83	13.09	15.25	13.65	13.96	-2.38
-2029.62	14.92	14.14	16.40	14.91	15.09	-3.51

[a] Negative sign (-) in load denotes an incremental load

[b] Negative sign (-) in movement denotes the pile head displacement towards upward

A graph is plotted based on the applied load and the pile head movement (Refer Figure 6).

The results of the strain test indicate that the maximum skin friction occurs in the pile foundation at depths between -7.77 m and -9.47 m from the Existing Ground Level (EGL). Typically, maximum skin friction is observed at the pile section that is in contact with dense, stiff, or consolidated soils. The soil investigation report for this pile location shows that the soil strata is denser between -7.50 m and -9.00 m. This correlation clearly explains that the maximum skin friction has occurred in the denser soil strata of this location. Additionally, based on the results of pile head movement, the maximum recorded pile head settlement was 3.51 mm at 2.0 times the working load (2029.62 kN), which is within acceptable limits. Therefore, this test provides a

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comprehensive examination to determine the pile load distribution, skin friction behavior along the pile shaft and pile head displacement under load, which remains a well-known and effective method for assessing these critical characteristics of the pile foundation.

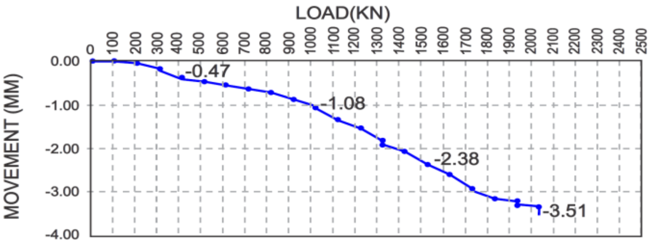

Fig. 6. Applied Load and Pile Head Movement

B. *Low Strain Pile Integrity Test*

Low-strain pile integrity testing (PIT) assesses pile continuity by analyzing stress wave reflections due to impedance changes along the shaft, following ASTM D5882 guidelines. The test measures and analyzes the velocity induced by an axial impact (e.g., from a handheld hammer) at the pile head to evaluate the integrity, dimensions, continuity, and uniformity of vertical or inclined piles as in [6]. However, this method does not provide insights into the pile's bearing capacity. The technique employed in this low strain integrity test is known as the Pulse Echo Method (PEM). This testing can be conducted on both working piles and test piles as in [7].

Apparatus

The force can be applied using a handheld hammer with a hard plastic tip to create brief input pulses under 1 millisecond, protecting the pile head. An accelerometer collects and integrates velocity data, which is transmitted for recording and processing. The system features a display and storage for analysis and can average data from multiple strikes to improve reliability and minimize noise from soil. Figure 7 shows an apparatus for applying impact and testing.

Fig. 7. Apparatus for applying impact and testing

Procedure

The 400 kV overhead transmission line runs between the Dubai Janub and Canal Garden BSP in the Dubai, United of Arab Emirates. This transmission line is approximately 47 kilometers long and consists of 110 towers, all of which are built on pile foundations. All the pile legs of tower foundations are tested for the Low Strain Integrity Test. However, for the study purpose, we will examine in this article only about few piles.

The test is performed using PIT Collector from Pile Dynamics, Inc. utilizes digital data acquisition equipment, a transducer, and a handheld hammer, following the Pulse-Echo Method. Before testing, ensure the pile is cut to its final height and at least seven days have passed since the concrete was cast. The pile head should be clean and free of water or loose material as in [8]. An accelerometer is attached to the top of the pile with Pietoplast for optimal signal transmission. A sharp impact is delivered from about 150mm above the pile, within 300mm of the accelerometer. Multiple impacts should be recorded, with velocity checks for consistency to guarantee data quality.

Interpretation of Test results

The test result interpretation must be conducted by a qualified Engineer. Using the Pulse Echo Technique, the measured velocity at the pile head is analyzed over time. The data displayed should feature the velocity records plotted against time, along with details of the pile length and assumed wave speed, as well as a visualization of the shape and magnitude of the amplification function when applicable. Pile integrity is assessed by monitoring changes in velocity after the initial impact, with a definitive toe signal and stable velocity trace indicating a sound pile as in [9]. Significant variations in velocity may result from alterations in pile cross-section, the quality of concrete, or soil resistance. In the absence of any changes in soil resistance, variations in velocity at the pile top are due to changes in pile impedance. The pile impedance (Z) is defined as,

$$Z = c \ \rho A = A \sqrt{E \rho} \qquad (6)$$

where, A is Cross sectional area of pile
c is Velocity of propagation of the stress wave through the pile
E is Modulus of Elasticity of concrete
ρ is Density of concrete

Consequently, a reduction in impedance can be attributed to either a decrease in area, a reduction in the concrete's modulus of elasticity, or a decline in density. Given that both modulus and density are associated with concrete strength, it can be concluded that impedance is influenced by the cross-sectional area and the quality of the concrete.

The calculation of the pile's acoustic length (L), or the depth of other intermediate features on the signal response curve, relies directly on the propagation velocity (c) as expressed in equation (7),

$$L = c\, t / 2 \qquad (7)$$

where, t is Time lapse between the first hammer impulse and the arrival of the returning reflected wave from the remote end of the pile.

The propagation velocity (c) for sound concrete is generally reported to range from 3700 to 4300 metres per second. For analytical purposes, a value of 4000 metres per second is often utilized. Deviations of the actual propagation velocity from that used in the calculated pile length derived from the signal-response curve are usually anticipated to be within 10% of the true value as noted in references [10] and [11]. The results obtained from the tested piles are displayed as averaged, amplified velocity versus time graphs. In Figure 8, depicting the sound pile, a distinct toe reflection is noticeable at a travel time that corresponds to the known length of the pile, without any significant intermediate reflections, suggesting consistent impedance throughout the shaft. On the other hand, Figure 9 shows an early reflected signal with considerable amplitude appearing before the anticipated toe reflection, indicating a potential alteration in pile impedance that could be linked to necking, cracking, or non-uniformity in the material.

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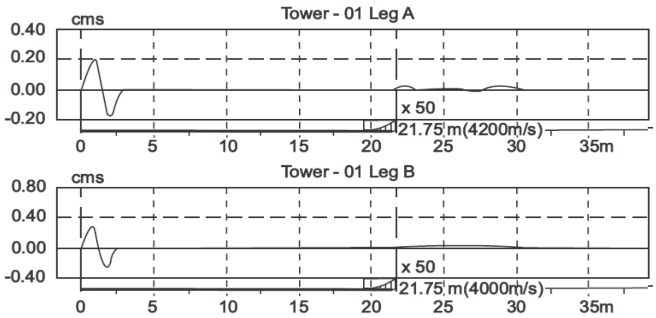

Fig. 8. PIT response for sound pile

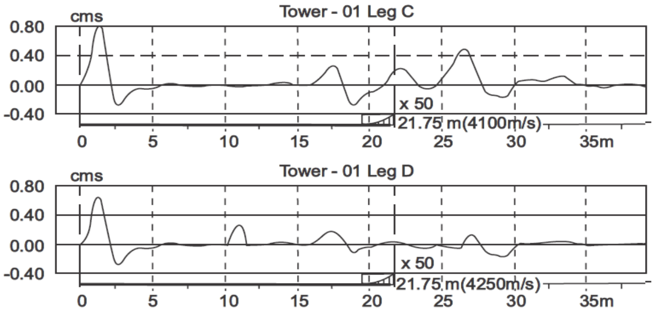

Fig. 9. PIT response for pile with suspected impedance change

According to the obtained test results, the following report can be made for the piles shaft tested (Refer Table V).

TABLE V. REPORT OF LOW STRAIN INTEGRITY TEST

Description of Pile	Pile Length, m	Status
Tower – 01 Leg A	21.75	AB
Tower – 01 Leg B	21.75	AB
Tower – 01 Leg C	21.75	PF
Tower – 01 Leg D	21.75	PF

The abbreviations utilized in the report are AB: (No Major or Minor Defect Indicated), which indicates the absence of a toe signal but does not imply any irregularities and PF: (Potential Flaw), which denotes a clear reduction in impedance, suggesting a void, necking, or soft soil inclusion.

The report confirms that there are no defects, either major or minor, found in the tested piles of Tower 01 (Legs A and B). However, significant velocity fluctuations and a reduction in impedance were observed in the tested piles of Tower 01 (Legs C and D). Further comprehensive testing, such as Cross hole Sonic Logging, CSL, is recommended for these legs. Generally, the PIT identifies relative changes in pile impedance and does not quantify defect size or distinguish structural defects from soil-induced impedance variations. Therefore, PIT results were interpreted in conjunction with construction records and instrumented load test data.

III. SUMMARY AND CONCLUSION

Piles are crucial for carrying heavy loads in construction, transferring them to stable soil layers. Before use, their performance and integrity must be assessed. This study evaluated a bored cast-in-situ pile for a transmission line tower using instrumented static load testing and low-strain pile integrity testing. The pile underwent axial loading of up to 2.00 times its working load (2029.62 kN). The maximum measured pile head settlement was 3.51 mm, indicating good serviceability. Strain gauge data revealed that most shaft friction mobilization occurred within the upper 9.00-10.70 m of the pile, increasing with applied load.

Low-strain pile integrity testing confirmed the continuity and uniformity of the pile shaft, with a distinct toe reflection corresponding to an effective pile length of approximately 21.75 m. No significant defects or cross-sectional irregularities were detected in two piles, while major suspected impedance changes were observed in the other two piles of a tower foundation. Conducting a CSL is recommended on the suspected piles to ensure their structural integrity.

In conclusion, vibrating wire embedment strain gauges provided a reliable means of evaluating pile load transfer behavior, shaft friction mobilization, and settlement characteristics. When combined with low-strain pile integrity testing, the integrated approach offers a comprehensive assessment of pile performance and structural integrity, contributing to the safe and durable design of pile foundations for transmission line tower structures.

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