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Original Research Article

# Field Installation and Performance Assessment of Prestressed High-Strength Concrete (PHC) Piles for the Steel Plate Manufacturing Project in Ras Al Khair

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## Abstract

This paper presents a case study of a pilot project on using novated Pre-Stressed High-Strength Concrete (PHC) Piles technology for a potential support to the large foundations of Steel Plate Manufacturing Plant, which to be installed on an area that contains sabkha soils saline, loose, and water-saturated sands in Ras Al Khair Industrial City, Saudi Arabia. The key highlight of this project is the successful installation and testing of Prestressed High-strength Concrete (PHC) piles likely the first such application within Saudi Aramco, and possibly within the Kingdom of Saudi Arabia. This paper presents the load-settlement and the load-displacement diagrams for the tested PHC piles and identifies the bearing capacity of some of these piles at the job site. The study summaries the bearing capacities of the tested PHC piles to be considered for the detailed design of future project packages. PHC Pile foundation reduces the settlement of structures and improves bearing capacity of foundation; and the new pile technologies are of little noise and reduce damage to pile during the installation. The PHC piles, characterized by a hollow core and prestressed concrete design, are typically produced with outer diameters ranging from 300 mm to 1200 mm and engineered to endure high axial loads and bending moments, making them suitable for challenging ground conditions such as sabkha.

**Keywords:** Prestressed High-Strength Concrete (PHC), Piles technology, Saudi Arabia, Aramco.



## 1.0.INTRODUCTION

Several studies have focused on precast prestressed high-strength spun concrete (PHC) piles, which are widely used for earthquake-resistant foundations. Following the 1995 Hyogoken-Nanby earthquake in Kobe, Japan, investigations of 111 piles on reclaimed islands revealed severe damage up to 8 m deep, with horizontal displacements of 250–420 mm caused by differential responses in sand layers [1, 2]. Further research on the shear performance of PHC piles under seismic loads, using experiments and finite element analyses, demonstrated that axial load and shear span-to-diameter ratio significantly affect shear strength and failure mode, in line with Japanese design guidelines [3].

In Northern Jakarta, 600 mm prestressed spun piles were studied using SPT-N data and finite element methods to predict load–settlement behavior. The analysis showed that reduced pile–soil interface strength decreases pile capacity, while key soil parameters were determined from site investigations [4]. Additionally, reviews of pile testing standards in Kazakhstan highlighted ASTM benchmarks, testing methods, equipment, and limitations to support the alignment of local practices with international standards [5]. Moreover, many of pile researchers are using and modifying pile related formulas to optimize with their actual field findings [6].

PHC piles are produced from heat-treated concrete, achieving compressive strengths exceeding 80 MPa, high density, low permeability, and excellent impact resistance [7]. Tensile strength is provided by steel reinforcement, tensioned wires, and fiberglass, with pre-stressing or post-tensioning reducing cracking and improving suitability for deep foundations in buildings, bridges, and other civil structures [8,9]. The Drilled PHC Pipe-Cased (DPC) method further minimizes construction damage, noise, and environmental impact, reflecting modern, energy-efficient foundation practices [9].

The piles of this project were installed and tested in Ras Al Khair, which is located in the Arabic Gulf. Gulf region's topography was formed by continuous sediment accumulation since the Paleozoic Era, with evidence showing that areas up to 100 km inland were once submerged under the sea. Extensive coastal sabkhas flat, salt-crusted plains of loose, saline, and water-saturated sand pose major foundation challenges due to their low strength and stability. Soil treatment was conducted at this area using Prefabricated Vertical Wick Drains (PVDs). The installation of wick drains accelerated consolidation, reduced settlement, and improved stability [10].

## 2.0. Installation Technologies and Procedures of PHC Pile

Driving, pressing, and boring (drilling) are the three methods for constructing PHC (Prestressed High Strength Concrete) piles. Driving uses hydraulic hammers or vibratory drivers to push the pile into the ground, whereas pressing uses hydraulic jacks for pile installation; and boring method drills borehole, inserts PHC pile then injects cement grout.

Driving method is fast, efficient and used for various type of soil. It increases soil bearing capacity by compacting the soil around the pile. However, it produces excessive noise and vibration. While pressing method is quiet, low-vibration and fast, however, it is not suitable for areas with underground obstructions and can crack and damage the pile. In the other hand, drilling method handles hard soil and minimizes disturbance to piles, however, it is not fast compared to driving or pressing method.

The PHC pile installation starts with surveying the job site, conducting soil test and analysis to determine the appropriated pile length and diameter together with the proper installation method, and marking the exact location for each PHC pile according to the design drawings. PHC pile is installed with one of the following methods:

1. **Driving:** A hydraulic crane lifts the pile and places it at the marked location. It uses a heavy impact hammer to drive PHC pile into the soil until it reaches the designed penetration depth. PHC piles is welded with another pile to extend its length.
2. **Static Pressing:** A hydraulic crane lifts the pile and places it at the marked location. It uses a hydraulic jack to exert pressure, and slowly press the pile into the ground until it reaches the designed depth.
3. **Drilling (Pre-boring):** A borehole is drilled, it is a little bit larger than the pile diameter and of the same pile length, and cement grout is injected into the borehole to stabilize the soil. The PHC pile is lowered into the borehole followed with pouring grout to fill the space between the pile outer diameter and the borehole inner area.

Pile shoes or funnel boots are used in some pile installation, but not in all projects. It is welded to the bottom of the pile to remove soil around the pile out through pile's internal cavity.

In our project, the PHC piles were installed and tested as per the ASTM standards. CPTU tests, Cone Penetration Tests, were conducted to determine the geotechnical properties of soils. Piezocone probes were pushed into the ground, mainly to measure soil properties such as penetration resistance of the cone, sleeve friction, and pore water pressure, all of these parameters were collected for better arrangement of pile design and installation. Pile rig was used to lift the pile, align it vertically with the ground, using theodolite instrument that measure both horizontal and vertical angles on pile's sides, before being positioned and installed. Additionally, special cushion was placed between pile head and driving hammer, which distributed the energy evenly, reduced damage and deformation of pile head and minimized produced noise and vibration.

## 3.0. Determination of PHC Pile Capacity Using Hilly Piling Formula

Hilly Piling Formula is used to determine Pile driving resistance. This dynamic pile driving formulae provide less accurate calculations of pile capacity compared to geotechnical design methods, however, they are still generally used in practice. The Hilly formula accuracy is reduced with longer piles and areas saturated with silts, muds, or clays.

**Common form of Hilly formula is:**

$$R = \frac{E}{s + c} \quad (1)$$

$R: Driving\ resistance$
$E:\ Hammer\ energy$
$S: Pile\ set\ (Penetration\ per\ blow)$
$C: Elastic\ compression\ and\ energy\ losses.$

**More complete form of Hilly formula is:**

$$Q = \frac{EH\eta}{S + \frac{C}{2}} \quad (2)$$

$Q: Ultimate\ load\ capacity\ of\ the\ pile, kN$
$E:\ Efficiency\ of\ the\ hammer\ , 0.7\ to\ 0.9$
$H: Height\ of\ hammer\ drop, m$
$\eta: Efficiency\ of\ energy\ transfer$
$S: Penetration\ per\ blow, mm$
$C: Total\ Elastic\ compression\ of\ pile, m$

The formula used in our project was driven from the basic formula of Hilly. It accounts for type of pile, pile length, cushion, soil, weight of pile and weight of hummer.

$$Q = \frac{Wh\eta}{S + C(W + w)/2} \quad (3)$$

$Q: Ultimate\ pile\ capacity\ per\ blow, kN$
$W:\ weightt\ of\ Hammer\ , kN$
$h: Height\ of\ hammer\ drop, m$

$\eta: Hammer\ efficiency$
$S: Penetration\ per\ blow, mm$
$C: Elastic\ compression\ and\ energy\ losses, m$
$w = Weight\ of\ pile, kN$

**4.0. Common Testing Methods for PHC Piles**

The most important tests which have to be conducted for PHC pile are static load tests, Dynamic load test and Pile integrity test:

1. **Static load testing (SLT):** Determine how much load a pile can support, by gradually applying and increasing load on a pile and measuring the displacement. It consists of Vertical Compression, Tension and Lateral tests. It determines actual load-bearing capacity of the pile. The load is applied using hydraulic jacks and gradually increased while the settlement is measured. The test is conducted according to ASTM D1143 –Standard Test Method for Deep Foundations Under Static Axial Compressive Load [11]. The loads are applied downward in Compression Test, uplift in tension test, and in horizontal direction in lateral test, to measure pile horizontal load resistance. The result of these tests is represented in Load versus Settlement curve, which helps to identify the safe working and ultimate loads capacities.
2. **High-strain dynamic load testing (DLT):** Assesses pile capacity using falling hammer, while strain gauge and accelerometer sensors attached to the pile, to measure force and velocity, which are read and analyzed by Piling Driving Analyzer (PDA). To clarify, the test estimates pile capacity using waves of stress from hammer impacts. The sensors are attached to pile head, pile is struck with a hammer and signals are received and analyzed using Pile Driving Analyzer (PDA). The test is conducted according to ASTM D4945 – High-Strain Dynamic Testing of Piles [12].
3. **Compression load tests:** Evaluate strength of material under crushing forces.
4. **Tension Test:** determines the strength and ductility of the pile.
5. **Lateral load tests:** Determine how a pile behaves when it is subjected to horizontal force.
6. **Pile integrity test,** known as low Strain Integrity Test: use Non-Destructive Test (PIT or Sonic Echo Test) to evaluate the continuity, length, deduct cracks, voids and necking in the pile. A small hammer taps the pile head and the reflected waves are captured and analyzed.
7. **Pile Driving Monitoring Test** monitors driving resistance, energy, and pile stress during installation, detects related cracks and damage, and confirms driving depth and final set.

**5.0. PHC Pile Axial Capacity Calculation**

Below is an example of theoretical design of a 10 m long, 400 mm PHC pile. It is prepared based on theoretical data and assumptions, while it requires real and site-specific geotechnical data including CPT tests.

Pile length: 10.0 m
Pile width (diameter): 0.40 m (circular)
Safety Factor = 2.0
1. Pile Geometry
Diameter D = 0.40 m
Length L = 10.0 m

$$Base\ Area\ of\ pile\ (End\ Area\ A_e) = \pi \frac{D^2}{4}$$
$$= \pi \frac{0.4^2}{4} = 0.1257\ m^2 \quad (4)$$
$$Shaft\ (Surface) Area\ A_s = \pi \mathrm{DL} = \pi(0.4)(10) = 12.5664\ m^2 \quad (5)$$
$$Ultimate\ Capacity\ Q_u = q_e * A_e + f_s * A_s$$
$q_e$ *is the end bearing resistance,* $(\frac{kN}{m^2})$

$f_s$ *is the skin friction (shaft resistance),* $(\frac{kN}{m^2})$
$$Working\ Capacity\ Q_w = \frac{Q_u}{Safety\ Factor\ (s_f)} \quad (6)$$

**Assumption for Soil Parameters:**
1. Soil Type: Dense sand
2. $q_e(\frac{kN}{m^2}) = 1200$
3. $f_s\ (\frac{kN}{m^2}) = 120$

Then;
$Q_e = 1200 \times 0.1257 = 150.80$ kN
$Q_s = 120 \times 12.5664 = 1507.96$ kN
$Q_u = 1658.76$ kN
$$Q_w = \frac{Q_u}{s_f} = 829.38 \text{ kN} \quad (7)$$

**6.0. Comprehensive Study on the Behavior and Testing Methods of PHC Piles**

The pilot project installs and tests 21 PHC piles with outer diameter and length varies from 400 mm to 600 mm and 10m to 12m, respectively. Total of 15 out of 21 piles passed all tests successfully, where 6 piles failed to meet the design capacity. This results on combinations of piles length, size and load capacity, to serve and optimize the design of pile foundations for the future packages.

This section presents and analyzes some of the conducted tests, which includes the followings:

**6.1.1. Pile Static Compression Load Test**

The purpose of the test is to verify the axial capacity of the pile by monitoring the load versus settlement. Dial gauges were used and settlement's readings were recorded for different applied loads to draw the load versus Settlement.

In this test, the load was applied in increments till reaching 200WL, and it was reduced gradually while the settlement reading was recorded as per ASTM D1143 Standard of Test Method for Deep Foundations Under Static Axial Compressive Load. Tables 1 and 2, contains the pile data, pile total and residual settlements.

**Table 1: The PHC pile data**

| Parameter | Value |
|---|---|
| Date of test | 18/03/25 |
| Pile No. | S-Z-1-8 |
| Pile Diameter | 500 mm |
| Pile Length | 11 m |
| Working Load | 2850 kN |
| Test Load | 5130 kN |
| Test equipment | Dial Gauges |
| | Theoretical Load |

The following table summarizes the total and residual average settlement.

**Table 2: Pile Settlement Summary Table**

| Parameter | Applied Load | Load (%) | Settlement |
|---|---|---|---|
| | 2850kN | 100% | 3.96 mm |
| | 5130kN | 180% | 34.44 mm |
| | 0 kN | 0% | 34.44 mm |

**Observations for S-Z-1-8:**

The tested pile was loaded to 180% (5130 kN) of the design working load. Its top was broken and the maximum settlement at working load was 3.96 mm; 34.44 mm at 180% WL and 34.44 mm after removing all loads.

The test indicates unacceptable and permanent pile damage. The pile has experienced large permanent settlement. This should be treated as failure for serviceability unless the project's acceptance criteria allow such large residual settlement. At the working load (2850 kN) the pile settled 3.96 mm, which is commonly acceptable for many designs. At 180% of working load (5700 kN) the pile settled 34.44 mm, and after unloading the pile, permanent settlement remained 34.44 mm with no rebound. A large residual settlement like this means the pile has undergone permanent deformation and indication of permanent damage.

ASTM D1143 defines the loading and unloading procedure, required hold times, and what to do if pile failure occurs. If failure occurs the procedure recommend to continue loading until settlement equals 15% of pile diameter, and that is an ultimate deformation criterion in the standard. 15% of diameter = 0.15 × 500 mm = 75 mm. 34.44 mm < 75 mm, so the test did not reach the ASTM 15% diameter ultimate deformation stopping point. However, not reaching 75 mm does not mean the pile is acceptable. Because permanent movement is large, the pile has been loaded beyond its elastic range (soil or pile yielded). The test therefore cannot be viewed as proving a safe elastic working capacity at 2850 kN without further evaluation. To clarify, ASTM does not advise a project acceptance settlement; allowable settlement has to be set by the design office and project specifications. More test data can be access from Figure 1, Load versus Settlement and Time for Pile SZ-1-8 and Figure 2, Load versus Settlement SZ-1-8.

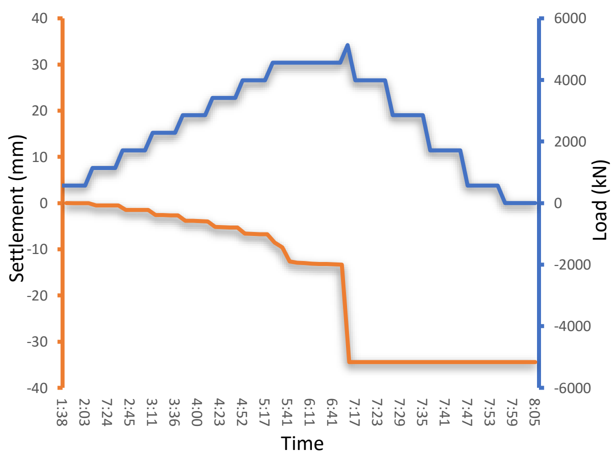



**Fig 1: Load vs. Settlement & Time for Pile SZ-1-8**

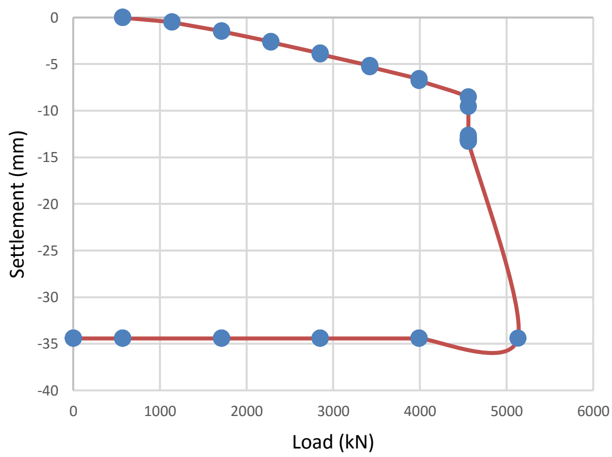



**Fig 2: Load vs. Settlement SZ-1-8**

### 6.1.2. Pile Static Compression Load Test

Tables 3 and 4, contains another pile data, pile total and residual settlements:

**Table 3: The PHC pile data**

| Parameter | Value |
|---|---|
| Date of test | 20/03/25 |
| Pile No. | S-Z-1-1 |
| Pile Diameter | 400 mm |
| Pile Length | 12 m |
| Working Load | 1750 kN |
| Test Load | 3510 kN |
| Test equipment | Dial Gauges |
| | Theoretical Load |

The following table summarizes the total and residual average settlement.

**Table 4: Pile Settlement Summary Table**

| Parameter | Applied Load | Load (%) | Settlement |
|---|---|---|---|
| | 1750kN | 100% | 4.48 mm |
| | 3510kN | 200% | 12.05 mm |
| | 0 kN | 0% | 3.40 mm |

The Settlement at working load (4.48 mm) seems to be reasonable for a PHC pile of this size, which is typically acceptable since it is below 6 mm. The Settlement at test load (3510 kN) is 12.05 mm, which is acceptable per ASTM D1143 since it is around 12 mm and below 8% of pile diameter. At the ultimate load test, the maximum settlement should be below 30 mm (8% of pile diameter).

$$Settlement_{recoverable} = Settlement_{test\ load} - Settlement_{unloading} \quad (8)$$

$$Settlement_{recoverable} = 12.05 - 3.40 = 8.65\ mm$$

$$Settlement_{maximum\ permenant} \leq \frac{1}{5}\sqrt{\frac{D}{\log D}} \quad (9)$$

$$D\ diameter\ in\ inch\ , 400\ mm\ = \ 15.748\ inches$$

$$Settlement_{maximum\ permenant} \leq \frac{1}{5}\sqrt{\frac{15.748}{\log(15.748)}}$$

$$= 0.725\ in = 18.4\ mm$$

A recoverable settlement of 8.65 mm indicates good elastic behavior. The pile has returned most of its deformation, showing no significant permanent deformation, which is acceptable. The pile settles 3.40 mm permanently, which is acceptable and per ASTM D1143 criteria. More test data can be access from Figure 3, Load versus Settlement and Time for Pile SZ-1-1 and Figure 4, Load versus Settlement SZ-1-1.

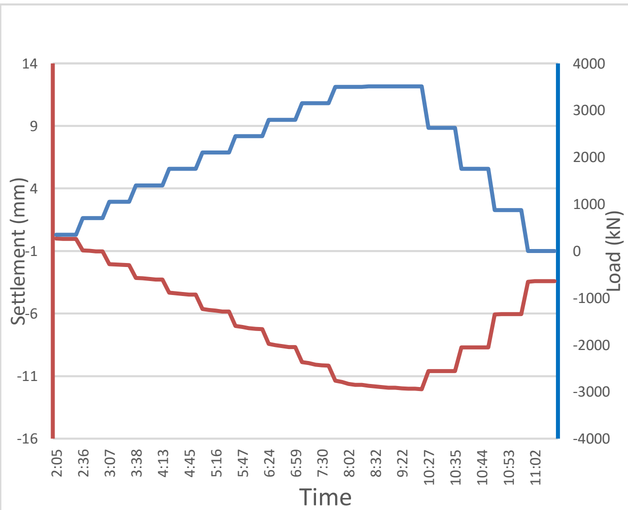



**Fig. 3: Load vs. Settlement & Time for Pile SZ-1-1**

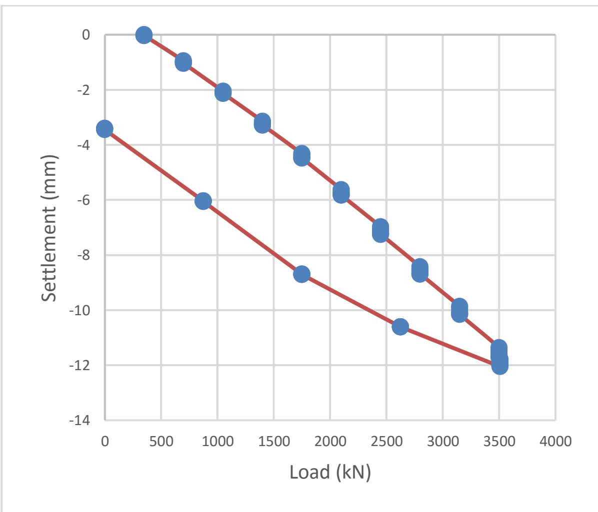



**Fig. 4: Load vs. Settlement SZ-1-1**

**6.2.1. High Strain Dynamic Testing of Piles**

The High Strain Dynamic load measurements were obtained for a number of Piles. The main purpose of this test is to estimate the bearing capacity, pile load carrying capacity, structural integrity, pile movement and pile-soil load transfer, through subjecting the pile to a dynamic load, monitoring, recording and analyzing its reaction. The dynamic testing procedure follows ASTM D4945 - Standard Test Method for High-Strain Dynamic Testing of Piles. PDA and CAPWAP were used to measure and analyze the collected data. The PDA is designed for real-time monitoring of deep foundation elements—such as driven piles. It captures strain and acceleration data while testing.

Prior to the start of the test, the pile head was prepared, cleaned, made flat and perpendicular to the pile axis. Testing instrumentation were installed - including Strain gauges to measure force and Accelerometers to measure velocity and acceleration. The PDA receives and saved the data from the instrumentations. To clarify, the strain transducer measures the force, it is bonded to a pile from one end and connected to data acquisition system from the other end. It generates voltage signal in proportion with the resulted strain of the applied loads, stress, and structural behavior. In this Dynamic test, two strain transducers and two accelerometers were installed using anchor bolts at a distance of 1.5 x pile diameters, below the pile head and opposite to each other. While the impact hammer is dropped on the pile head, the generated compression wave travels down the pile and reflects from the pile-toe upward, wave data is picked up by the sensors, processed and recorded in the PDA equipment and used later for further analysis and graphical presentations.

Tables 5 includes tested pile data:

**Table 5: The PHC pile data**

| Parameter | Value |
|---|---|
| Date of test | 12/29/25 |
| Pile No. | S-Z1-6 |
| Pile Diameter | 500 mm |
| Pile Length | 10 m |
| Top Level | 3.28 m |
| Toe Level | -6.72 m |
| Working Load | 2,850 kN |
| Test Load | 5,700 kN |
| Test equipment | Strain gauges |
| | Accelerometers |
| | Pile Driving Analyzer (PDA) |
| | Case Pile Wave Analysis Program (CAPWAP) |

This test was conducted using a free-falling hammer with ram weights of 6 ton, released vertically from 70 to 110cms height on the pile top, which was protected with plywood cushion. During the test, dynamic stress wave speed for the pile was recorded to be 4000 (m/s). Considering concrete specific weight of 25.0 kN/m³ and the stress wave speed of 4000 (m/s), the dynamic elastic modulus for the concrete in the pile was calculated to be 40789 kN/cm².

The PDA's recorded force, velocity waves and data are used by CAPWAP to simulate the force-time response at the pile head, and estimates the total static capacity, skin friction, end bearing, pile toe and shaft resistance distribution.

**Test Analysis:**

The activated total static, skin friction and toe resistance capacity, as well as the pile top deflection at the activated capacity for the piles are listed in Table 6; and the settlement at the corresponding static applied loads in Table 7.

**Table 6: Deflection Readings**

| Parameter | Value |
|---|---|
| Pile No. | S-Z1-6 |
| Pile Diameter | 500 mm |
| Pile Length | 10 m |
| Activated Total Static Capacity | 5,841 kN |
| Activated Skin Friction Capacity | 653 kN |
| Activated Toe Resistance Capacity | 5,188 kN |
| Deflection at Activated Capacity, Dx | 25.1 mm |
| Dx: maximum deflection at max. Capacity. | |

**Table 7: Settlement Readings**

| Parameter | Settlement |
|---|---|
| 2,850 kN – WL | 9 mm |
| 5,700 kN – 2xWL | 22 mm |
| 0 kN | 0.9 mm |

The total static capacity activated is 5,841 kN, which is more than twice of the working load (2,850 kN), indicating an excellent safety margin. Activated toe resistance is 5,188 kN and activated skin friction is 653 kN, which indicate toe-dominant, and that is typical for driven PHC piles in stiff soils or rock-bearing layers.

The Settlements are ~9 mm at working load, ~22 mm at test load and 0.9 mm permanent settlement. All settlement values are within acceptable limits, indicating elastic behavior, and no significant residual deformation. The high elastic modulus 40,789 kN/cm² reflects the pile's excellent stiffness.

The Pile has adequate bearing capacity and significant safety margin with controlled and recoverable settlement behavior under both working and test loads and predominant end-bearing behavior. It is considered accepted according to ASTM D4945.

Figure 5 illustrates the test, Load versus the Displacement, how much the pile moves with applied dynamic force, example, the Displacement is 25mm at 5,841 kN applied load. Figure 6 includes photo of the test from the field.

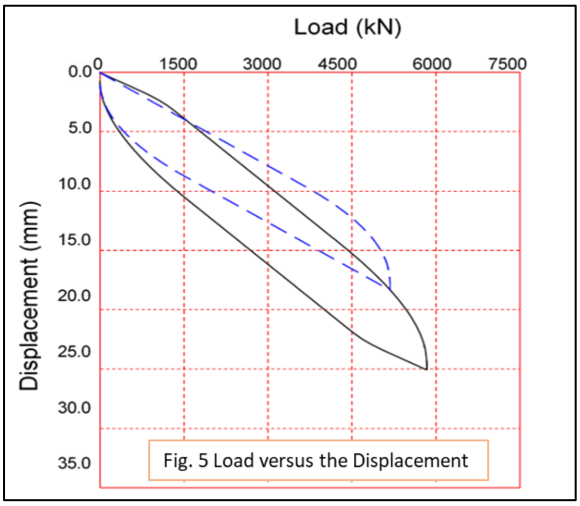


Fig. 5 Load versus the Displacement

**Fig. 5: Load versus the displacement**

**Fig. 6: Field Test**

**6.3.1. Lateral Load Test - PHC Pile Ø 500mm, L=12 m.**

The lateral load test was used to measure the deflection of the PHC pile with respect to lateral loads and to evaluate the actual soil resistance at the site. Pile deflection is the horizontal displacement of a pile under an applied lateral force. The readings of dial gauges were recorded during pile static lateral load test throughout different loading stages - as the test load incrementally increases - and data were used to draw the Load versus Deflection and Time. This test was conducted according ASTM D3966, Standard Test Methods for Deep Foundation Elements Under Static Lateral Load [13]. Tables 8 includes tested pile data and Table 9 contains pile deflection summary.

**Table 8: The PHC pile data**

| Parameter | Value |
|---|---|
| Date of test | 06/04/25 |
| Pile No. | S-Z-1-1 |
| Pile Diameter | 500 mm |
| Pile Length | 12 m |
| Working Load | 100 kN |
| Test Load | 200 kN |
| Test equipment | Dial Gauges |
| | Theoretical Load |

**Table 9: Pile Deflection Summary**

| Parameter | Applied Load | Load (%) | Deflection |
|---|---|---|---|
| | 100 kN | 100% | 6.99 mm |
| | 200 kN | 200% | 30.20 mm |
| | 0 kN | 0% | 16.84 mm |

The maximum deflection at working load is 6.99 mm, which is acceptable. The deflection at the test load is 30.20 mm. The acceptable deflection at test load as per some specifications is 25–50 mm, most likely the reason of the high deflection is the deformation of the soil properties near this pile surface, which needs to be improved.

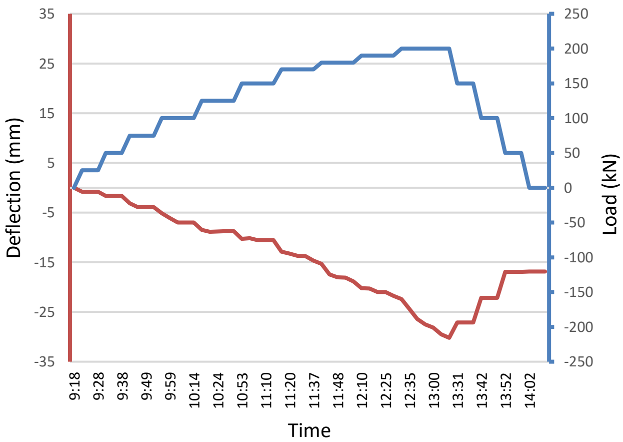



**Figure 7: Shows the Load versus Deflection and Time**

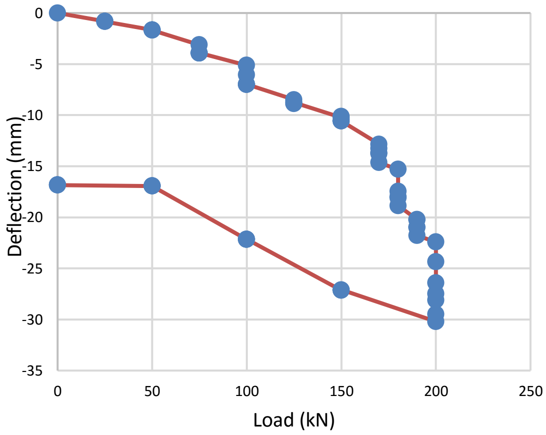



**Figure 8: Presents the Load versus the deflection of the pile**

### 6.3.2. Lateral Load Test

Table 10 contains data related another tested pile.

**Table 10: The PHC pile data**

| Parameter | Value |
|---|---|
| Date of test | 08/04/25 |
| Pile No. | S-Z-1-7 |
| Pile Diameter | 500 mm |
| Pile Length | 12 m |
| Working Load | 100 kN |
| Test Load | 200 kN |
| Test equipment | Dial Gauges |
| | Theoretical Load |

Table 10 summarizes the deflection results of the tested pile.

**Table 11: Pile Deflection Summary**

| Parameter | Value | Load (%) | Deflection |
|---|---|---|---|
| Applied Load | 100 kN | 100% | 2.17 mm |
| | 200 kN | 200% | 7.57 mm |
| | 0 kN | 0% | 1.82 mm |

The maximum deflection at Work load is 2.17 mm and at the test load is 7.57 mm, which is acceptable. Deflection at Test Load is more than triples the deflection at Work load. This indicates nonlinear or plastic behavior. After unloading to 0 kN, there is a residual deflection of 1.82 mm shows. It means that the pile experienced some permanent deformation, however, it is small and could be accepted.

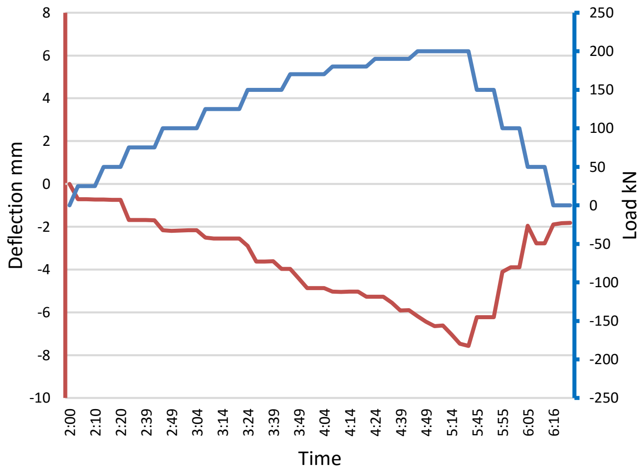


**Figure 9: Presents Load versus Deflection and Time**

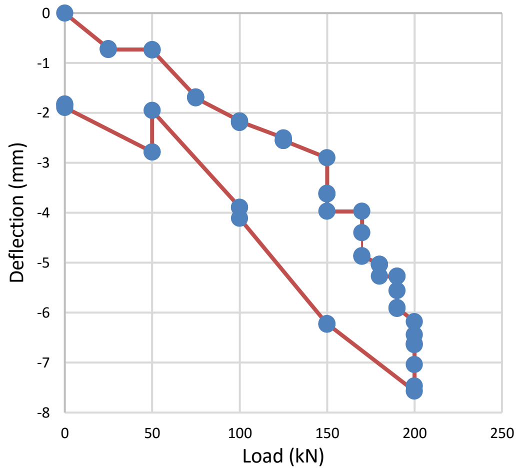


**Figure 10: Illustrates Load versus Deflection of the pile**

**6.4.1. Tension Load Test Analysis**

The tension pile test could be conducted in one of two ways, either by applying load gradually or by pulling the pile upward at a constant speed while the force required to maintain that speed is continuously measured and recorded together with the pile displacement. The piles shall have necessary structural strength to transmit the loads imposed on it to the soil.

This Tension Load Test measures the displacement of the pile up to 200% of working load. The test was conducted at different loads and displacement readings were recorded using dial gauges. This test was performed according to ASTM D3689, Standard Test Method for Deep Foundations Under Axial Tension Load [14].

**Table 12: The PHC pile data**

| Parameter | Value |
|---|---|
| Date of test | 20/04/25 |
| Pile No. | S-Z-1-13 |
| Pile Diameter | 600 mm |
| Pile Length | 11 m |
| Working Load | 250 kN |
| Test Load | 502 kN |
| Test equipment | Dial Gauges |
| | Theoretical Load |

The summary of the test and displacement is reflected in Table 13.

**Table 13: Pile Displacement Summary Table**

| Applied Load | Load (%) | Displacement |
|---|---|---|
| 250 kN | 100% | 0.14 mm |
| 502 kN | 200% | 1.60 mm |
| 0 kN | 0% | 0.55 mm |

**Displacement vs Settlement:**

Displacement means how much the pile head moves down when a load is applied. It includes both temporary and permanent movements. While, Settlement is the permanent movement that remains after the load is removed.

$$\text{Displacement} = \text{Elastic Movement} + \text{Settlement} \quad (10)$$

Elastic movement: recovers after unloading

Settlement: stays after unloading

**Observations:**

The maximum displacement at test load is 1.60 mm and the Residual displacement is 0.55 mm - after unloading. The Incremental Stiffness is ~173 kN/mm, between working and test load. It increases after unloading to be 478 kN/mm.

$$k = \frac{502 - 250}{1.60 - 0.14} = 173\ kN/mm$$

$k = Incremental\ Stiffness\ (between\ 250kN\ and\ 502kN)$

$$k_{unload} \simeq \frac{502-0}{1.60-0.55} = 478\ kN/mm$$

$Pile\ recover\ after\ unloading\ with\ a\ small\ displacement\ of\ 0.55mm$

The percentage of recoverable displacement: ~65.6%

$$Recoverable\ dispalcement = 1.60 - 0.55 = 1.05\ mm$$

$$Recovery\ \% = \frac{Recoverable\ dispalcement}{Maximum\ dispalcement} = \frac{1.05}{1.60} \simeq 65.6\% \quad (11)$$

To summarize, the maximum measured displacements are 0.14 mm at work load, 1.60mm at test load, and 0.55 mm after unload, as residual (permanent) displacement. These values are commonly accepted in Asia, since the residual displacement is ≤ 6 - 10 mm and total movement at the test load is ≤ 2% of pile diameter (12 mm for 600 mm pile). Accordingly, the tested PHC pile is accepted since it demonstrates excellent elastic behavior under the applied tensile load, with a small permanent displacement. Figure 11 present Load versus Displacement of the tested pile.

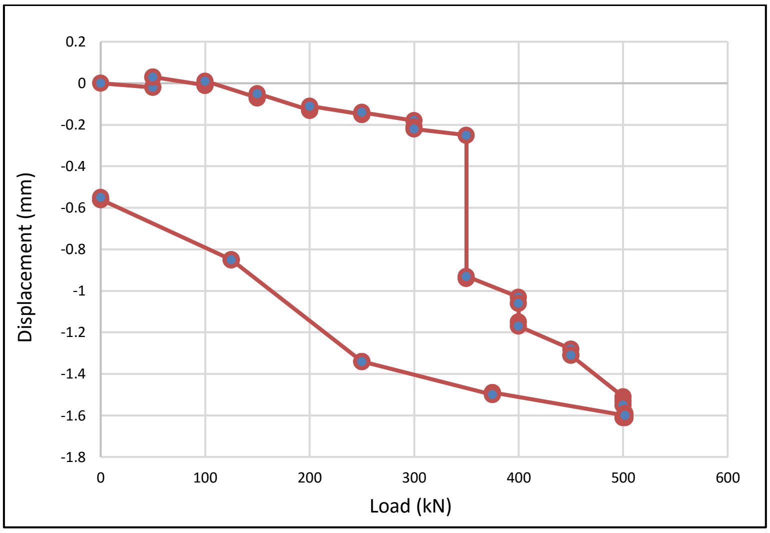
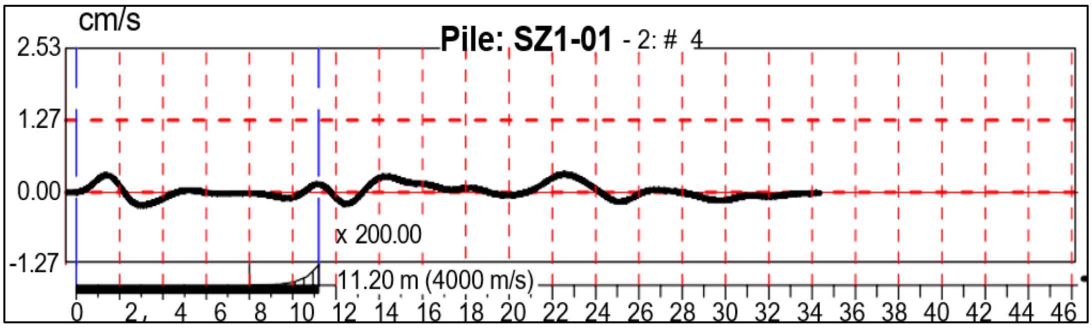



**Fig. 11: Load versus Displacement for Pile SZ1.13**

### 9.0. Pile Integrity Test (PIT)

The Low Strain Integrity test called, Pile Integrity Test (PIT) test, is generally carried out using one or two accelerometers, attached to the pile head from one end and to data acquisition unit from other end; and a hand-held hammer to induce impact. During this test, the handheld hammer taps the pile head gently causing low-strain stress waves that propagates through the pile and reflects back from defects or pile toe. The accelerometer measures the velocity of the generated waves and PIT Device (analyzer) receives and interprets the signals from the accelerometer. This test is conducted according to ASTM D5882-16 - Standard Test Method for Low Strain Integrity Testing of Piles [15] and no major structural defects were observed.

Test result indicates sound shaft integrity, as a clear toe reflection can be identified corresponding to the reported length and acceptable range of wave speed.




## 10.0. CONCLUSION

The paper presents the results of the pilot project that involves the installation of Prestressed High-Strength Concrete (PHC) piles and demonstrates the practical effectiveness of PHC pile design and material enhancements developed in response to the Hyogoken–Nambu (Kobe) earthquake. These improvements were aimed at increasing pile ductility, durability, and overall performance under combined axial, lateral, and uplift loading conditions. A series of comprehensive field and laboratory investigations—including Static Load Tests (SLT), Dynamic Load Tests (DLT), Lateral Load Tests, Tension Tests, and Pile Integrity Tests—were performed to assess the behavior and performance of the installed piles. The results confirmed that the enhanced PHC piles exhibited acceptable performance within the defined project specifications. The measured settlements and deflections were well within the tolerances established for serviceability for a number of tested piles, indicating satisfactory pile–soil interaction and load transfer mechanisms. While ASTM standards provide standardized methodologies for conducting pile load tests, they do not explicitly define acceptance limits for settlement or deflection. Accordingly, project-specific performance criteria were adopted to interpret the test outcomes. Load–settlement and load–deflection relationships, plotted for some of test samples, revealed consistent trends that align with theoretical predictions and empirical correlations from prior research. Overall, the findings validate the structural and geotechnical adequacy of the enhanced PHC pile system. The results support its applicability for full-scale implementation in similar geotechnical environments, offering a reliable foundation solution capable of withstanding design loads and maintaining serviceability under varying field conditions. Future studies focusing on long-term monitoring and seismic performance evaluation are recommended to further substantiate the durability and resilience of these upgraded pile systems.

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