

Preliminary Test Piles in Weak Weathered Lias Group Jurassic Mudstone Rocks

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ABSTRACT: This paper presents the findings from preliminary test pile investigations conducted in weak weathered Lias Group Jurassic Mudstone Rocks, as part of the High Speed Two (HS2) Phase One C23 contract. The primary objective of the study was to assess the behaviour of bored piles formed in Charmouth Mudstone under axial loading and to provide valuable insights into the most appropriate design methodology. The campaign included four Preliminary Test Piles, supported by a detailed, site-specific ground investigation that combined in-situ and laboratory testing. The paper discusses the challenges posed by the unique characteristics of the mudstone, compounded by the limited available guidance on this material. It examines the impact the behaviour of the geological unit has on pile capacity as it transitions from a completely weathered state, acting as clay, to a structured weak rock. The paper also critically reviews the applicability of commonly used pile design approaches for weak rock, as found in the literature and industry practices, comparing them against actual data derived from pile testing. Additionally, the study aims to contribute further to the body of published data on pile tests conducted on weak rocks in the UK.

KEYWORDS: Weak Lias Group Mudstone Rocks, Charmouth Mudstone, Pile Design, Preliminary Test Piles

1 INTRODUCTION

The High Speed Two (HS2) project is a 230km high-speed railway line currently under construction in the UK between London and Birmingham. The C23 contract has been awarded to Eiffage, Kier, Ferrovial Construction and Bam Nuttall (EKFB), a joint venture of international civil engineering construction contractors which in turn appointed a design joint venture made up of Arcadis, Setec, and COWI (ASC) to provide design services and construction support for the works.

The C23 contract consists of an 80km section which includes 30 mainline cuttings, 45 mainline embankments, 15 viaducts and 7km of cut and cover green tunnels to be constructed as part of the works.

This paper examines the results of four preliminary test piles carried out in Charmouth Mudstone, reviews the pile capacity and compares the results with commonly used pile design approaches for weak rock. In doing so, the authors aim to contribute further to the body of published data on pile tests conducted on weak rocks in the UK.

2 THE TRIAL SITE AND GROUND CONDITIONS

The preliminary test piles were carried out in 2021 on a test site situated between Upper Boddington and Wormleighton within the HS2 working area, Figure 1. A total of four Preliminary Test Piles (PTP) were carried out.

The wider geological setting comprises Jurassic strata composed of the Charmouth Mudstone Formation, overlain by superficial deposits. The Charmouth Mudstone Formation is a lithostratigraphic unit within the Lias Group and is predominantly composed of dark grey, fissile mudstones with interbedded siltstones, calcareous nodules and argillaceous limestone beds. The formation reaches thicknesses exceeding 300 m in some areas and conformably overlies the Blue Lias Formation.

The site-specific ground conditions of the test site are presented in Table 1 and comprise Head Deposits underlain by Weathered Charmouth Mudstone Clay (Grade C to E) followed by Extremely Weak to Weak Charmouth Mudstone (Grade A to B) and interbedded with a medium strong limestone band separating the interface between the Mudstone Clay to Mudstone Rock. The weathering profile of the Mudstone was

recorded in accordance to BS 5930:2015+A1:2020 ‘Approach 4’, for weak rocks.

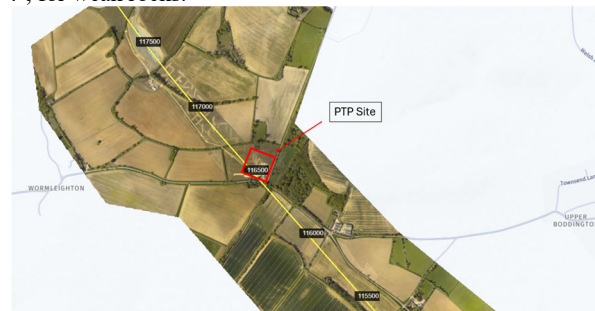


Figure 1. Boddington Preliminary Test Pile site

Table 1. Geological setting of the test site

Stratum	Thickness [m]
Head Deposits/Alluvium*	1-2
Weathered Charmouth Mudstone (Grade C to E)	5-6
Charmouth Mudstone (Grade A to B)	Proven to 47m

*groundwater recorded at ground level (most unfavourable).

Extensive in-situ and laboratory testing was conducted near the test piles. Figure 2 presents these results as undrained shear strength profiles for Charmouth Clay and Mudstone strata. Noting that only Stage 1 ground investigation (GI) data shown were available when specifying the pile tests.

3 TESTING CAMPAIGN SPECIFICATION

3.1 Test pile design

Four preliminary test piles were installed at the Boddington test pile site to verify the design assumptions of the axial load capacity of bored pile in the Charmouth Mudstone. Two were intended to inform the design of compression piles, PTP05 and PTP06 and two for the design of heave (tension) piles, PTP08 and PTP09. The load test was undertaken using Osterberg Cells (O-Cell) positioned at predetermined elevations along the lengths of the pile shaft. The design level of the bidirectional O-Cell, the test method and the test loads were aimed to mobilise the pile sections to ‘failure’ for the purpose of the test. Table 2 presents the test and design characteristics for each pile.

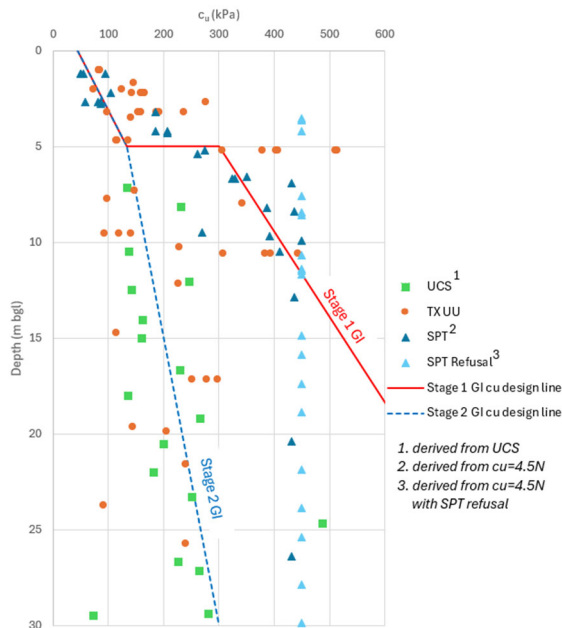


Figure 2. Undrained shear strength of the top 30m of the test site

Table 2. Test piles details

Pile	Dia [mm]	L [m]	Perm C [m]	DVL [MN]
PTP05	1500	20.0	-	7.2
PTP06	1500	20.0	-	7.2
PTP08	900	50.2	26.1	2.5
PTP09	900	50.2	26.1	4.3

DVL= design verification load, Dia=diameter of pile, L=length of pile, Perm C = permanent casing

Sister bar vibrating wire strain gauges were installed at multiple levels along the pile to determine the load distribution throughout the shaft. Arranged in sets of four at 90-degree intervals, these gauges provided redundancy in case of damage or failure. Expansion of the O-Cells was measured using linear vibrating wire displacement transducers, while telltale extensometers recorded compression in the pile sections above and below the O-Cells. To monitor top-of-pile displacements, Linear Voltage Displacement Transducers (LVDTs) were mounted on a steel box beam reference system supported by concrete foundations. Figure 3 and 4 illustrate the placement of the O-Cells and strain gauges for the two typical arrangements.

Thermal Integrity Profiling (TIP) tests were conducted on all piles using thermal wire sensors. Prior to installation, four thermal wire cables were secured along the entire length of each pile's reinforcement cage. For the larger-diameter piles (PTP05 and PTP06), additional Cross-Hole Sonic Logging (CSL) tests were performed. In all instances, the testing revealed no detectable defects or irregularities.

The two 1500mm diameter test piles were constructed with a short 6m temporary casing and bored without support fluid to the toe level before completing the piles via tremie operation due to some water ingress. A single level of O-Cell was installed to introduce bidirectional load to the test piles. Figure 3 shows the schematic sections of the test piles together with strain gauges and extensometers installed to provide load distribution along the piles during the tests.

For the two 900mm diameter test piles, a 26.1m long sleeve was grouted into a 1200mm diameter pile bore well before the piles were bored using 900mm diameter tools and concreted under tremie operation. In these test piles, two levels of O-Cells were installed in order to provide an understanding of the distribution of the pile resistance including the

performance of the bitumen coated sleeve of the pile. The test of the bitumen coated sleeve was intended to provide validation of the friction reduction performance of a bitumen coating intended to reduce potential heave force on piles installed in deep cuttings in the Charmouth Mudstone. Figure 4 shows the schematic sections of the test piles together with strain gauges and extensometers installed to provide load distribution along the piles during the tests. Figure 5 shows the application of the bitumen coating on the steel casing which forms the sleeve of the test pile.

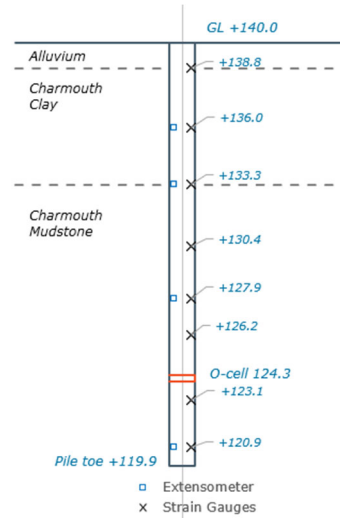


Figure 3. Instrumentation of test piles and O-Cell arrangement for compression test piles

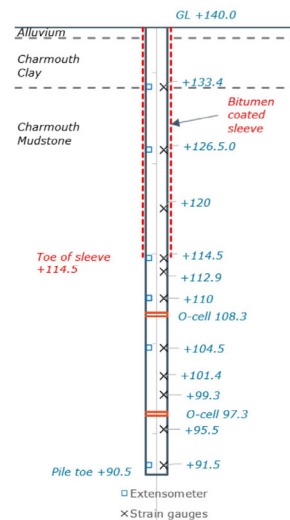


Figure 4. Instrumentation of test piles and O-Cell arrangement for heave test piles

3.2 Test pile construction and testing procedure

The load bearing section of the test piles (full section of the compression pile and pile length below the toe of the sleeve for heave pile) were bored and cast in a single day. It was anticipated that construction of the test piles would be undertaken in the dry. However, during construction groundwater ingress was observed especially in the 900mm diameter test piles in the more competent mudstone. In PTP08

at remeasure of the final depth before concreting the pile observed 600mm of debris at its base. GoPro inspection of the pile bores showed smooth shaft surface of the 1500mm diameter test piles while the deeper 900mm diameter test piles showed rougher surfaces caused by the groundwater ingress and drilling disturbance, see Figure 6 below.



Figure 5. Bitumen coating application on permanent casing



a) PTP06



b) PTP09

Figure 6. GoPro still images for the test piles

For the single level O-Cell test pile, a load proportional to the design load was applied with prespecified hold stages during the test. This was continued until failure of one part of the test pile, either upward or downward.

For the two levels O-Cell test, the sequence of loading is slightly more complex. When loading the top level of the O-Cell, the lower O-Cell was left open initially and the test sequence allowed it to be closed if reaction was needed. This procedure was repeated when load was applied to the lower set of O-Cell.

4 INTERPRETATION OF RESULTS

4.1 Reference pile design

A reference pile design was carried out to inform the testing regime and compare with the pile test results. This considered a thin 1.2m Head/Alluvium deposits layer over 5.4m of weathered Charmouth Mudstone followed by Charmouth Mudstone proven to 47m in thickness. The design of the test piles was based on conventional approaches used in the industry, with the following assumptions:

$$f_{s,k} = \alpha c_u \leq 125 \text{ kPa} \text{ or } f_{s,k} = a \sqrt{q_u} \leq 250 \text{ kPa}$$

$$f_{b,k} = 9c_u \text{ or } 3UCS$$

where $f_{s,k}$ = unit shaft friction

$f_{b,k}$ = unit base resistance

α = adhesion factor 0.5 for weathered mudstone

c_u = undrained shear strength for weathered mudstone and mudstone with low UCS, i.e. 0.5UCS

a = correlation constant 0.225

q_u = unconfined compressive strength of mudstone

Table 3. 1500mm diameter test pile design

Stratum	Elevation (mOD)	c_u (kPa) ¹	Average c_u (kPa)	Average $f_{s,k}$ (kPa)
Charmouth Clay	+138.8 to +133.4	44 + 18z	92	46
Charmouth Mudstone	+133.4 to +119.9	300+22.5z ²	450	225 (limited to 125)

¹Where z is depth from ground level

² Due to initial lack of ground investigation data, point load tests and sporadic SPT and triaxial tests were used to derive an equivalent undrained shear strength of the Charmouth Mudstone

Table 4. 900mm diameter test pile design

Stratum	Elevation (mOD)	UCS (MPa)	Average $f_{s,k}$ (kPa)
Bitumen coated sleeve	+140.7 to +114.5	-	20
Charmouth Mudstone	+114.5 to +90.4	2.0	318 (limited to 250)

4.2 Test Results

The distribution of the measured shaft resistance of these test piles is shown in Figure 7 and summarized in Table 5.

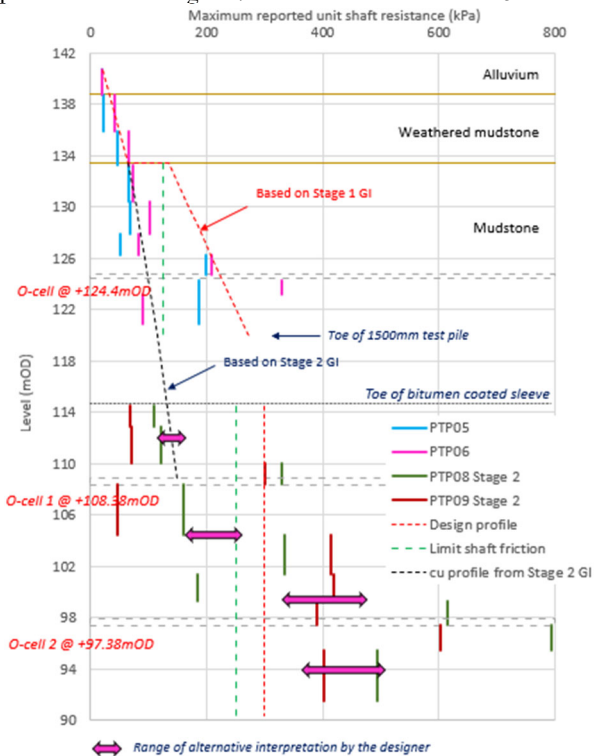


Figure 7. Distribution of measured shaft resistance of test piles at Boddington test site

Table 5. Test piles design and measured capacities

Pile	Design [MN]			Measured [MN]		
	Shaft	Base	Total	Shaft	Base	Total
PTP05	15.0	2.0	17.0	9.4	4.0	13.4
PTP06	15.0	2.0	17.0	11.1	5.1	16.2
PTP08 ¹	13.5	-	13.5	25.3	<1 ²	25.3
PTP09 ¹	13.5	-	13.5	22.6	1	23.6

¹ Test piles sleeved with 26.1m 955mm OD bitumen coated casing, designed to 20kPa shaft resistance but measured max value 50kPa

² Pile cast with a soft base

1500mm diameter test piles

For the 1500mm diameter test piles the measured unit shaft resistance in the Mudstone below a level of +133.4mOD was significantly lower than the calculated values representing a reduction of the α value adopted in pile friction calculation from

0.5 to 0.3. Such low measured shaft resistance from the test pile could be due to the smooth surface observed during installation and a lack of groundwater inflow to roughen the pile shaft. The equivalent pile head load-settlement behaviour of these two test piles extrapolated using the CEMSET program is shown in Figure 8.

At the time the test pile was designed and tested, the shaft resistance of the test pile below the level of +133.4mOD was based on limited Stage 1 GI data. Subsequently, additional detailed design GI was procured and additional UCS tests were undertaken on core samples. These tests show increasing UCS values from 260kPa at the top of the mudstone to 460kPa at the toe of the 20m long pile, or an average UCS value of approximately 350kPa in the section of pile below +133.4mOD. Using the pile design approach for a weak rock (Horvath & Kenney 1979, presented in 4.1), the corresponding shaft friction value would be approximately 115 to 152kPa with a representative value of 130kPa. This is still higher than the measured shaft resistance from the 1500mm test piles. When the UCS values were converted to undrained shear strength, c_u , the c_u values increase from 130 to 230kPa. Using the αc_u design approach, the equivalent shaft friction value increases from 65 to 115kPa with an α value of 0.5. This matches reasonably well with the measured shaft resistance values of the two test piles. However, when the same approach is extended into the mudstone further down, the measured shaft resistance is much higher than the calculated value based on αc_u design approach.

The ultimate shaft resistance of these test piles could be represented using the β design approach (also known as the effective stress approach), i.e. $f_s = \beta \sigma_v'$, where the β value is a constant appropriate for the soil, in this case the Charmouth Mudstone. This approach was adopted by Markyukaj *et al.* (2023) for weak Mercia Mudstone in the HS2 project further north of the Boddington test site. When superimposed onto the Charmouth Mudstone test piles results, a β value of 0.8 seems to fit well with the interpreted shaft resistance value, see Figure 9.

900mm diameter test piles

For the 900mm diameter test piles using multiple O-Cells, the measured unit shaft resistance in the Mudstone above the top O-Cell between +108 and +114mOD was well below the limiting value of 125kPa. However, below the top O-Cell the measured shaft resistance was generally well above the limiting value of 250kPa. For both tests, the mode of displacements did not allow full mobilisation of the shaft resistance of the portion of the pile shaft between the two O-Cells, i.e. when the load was applied to the top O-Cell the observed mode of failure was upward displacement whereas when the lower O-Cell was loaded the observed mode of failure was downward therefore did not allow full mobilisation of the shaft resistance of the middle section of the test pile between the two O-Cells. It is likely that the actual shaft capacity of the pile is higher than the interpreted values if the resistance of the middle shaft is fully mobilised.

When the β design approach is applied to this longer 50m length pile, the vertical effective stress, i.e. σ_v' , at the toe of the test piles is approximately 500kPa therefore the corresponding unit shaft friction value is $\beta \sigma_v' = 400$ kPa. This fits reasonably well with the average value of the longer piles, see Figure 7.

5 CONCLUSIONS

Three design methodologies were used to back analyse the measured capacity of preliminary test piles installed in Charmouth Mudstone at the Boddington test site, namely the clay αc_u , rock UCS and β design approaches. It is concluded

that the β design approach with β value of 0.8 shows a better fit to the test data obtained from the HS2 project site studies.

As for the bitumen coated casing, a measured shaft friction of 50kPa was recorded which was considerably greater than the 20kPa originally anticipated.

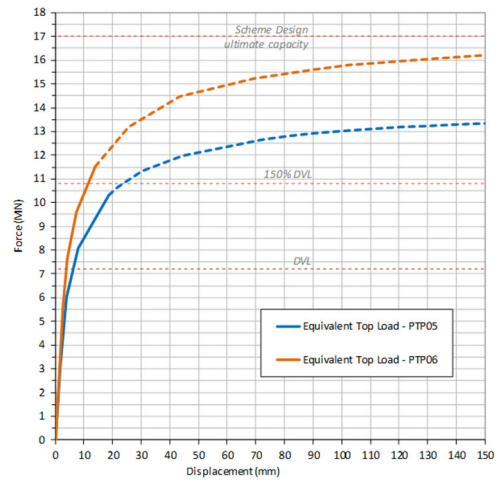


Figure 8. Equivalent pile head load-settlement for PTP05 and PTP06

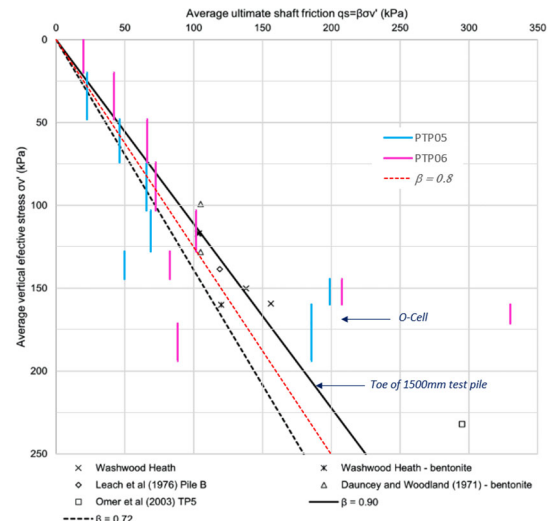


Figure 9. Interpretation of test piles in Charmouth Mudstone using the β design approach, superimposed onto Mercia Mudstone test data (Markyukaj S *et al.* 2023)

6 ACKNOWLEDGEMENT

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