Trial Piles and Foundation Design in Meta-sedimentary Rocks

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ABSTRACT

The rapidly developing Northern Metropolis (NM) is situated in a geologically complex region in Hong Kong where clastic sedimentary rocks being affected by metamorphism are present. Due to extensive folding, faulting and weathering, meta-sedimentary (MS) rocks in the NM are found to be highly variable in nature. However, there is a general lack of geotechnical information for those MS rocks mainly because of minimal urban development in the region so far. As there will be a surge of development works within the region in the coming few decades, the Geotechnical Engineering Office (GEO) recently initiated a large-scale pile loading test programme with a view to collecting extensive field data on end-bearing capacity and rock socket shaft resistance of various types of MS rocks in the region. The key objective is to explore room for enhancing the prevailing foundation design guidelines for MS rocks, thereby facilitating material and cost saving of the associated foundation works. As part of the study, some trial piles are strategically designed to investigate the constructability and performance of using eco-friendly Ground Granulated Blastfurnace Slag (GGBS) and high-strength S690 steel section in piling works. The study outcome would facilitate the wider application of these new and green materials for the benefit of advancing sustainable and cost-effective geotechnical solutions. While the pile loading tests are actively on-going, this paper reports the preliminary findings of the trial piling works, including bi-directional loading tests on instrumented piles, the applications of high-percentage GGBS concrete and grout as well as S690 steel section in pile foundations.

1 INTRODUCTION

The Northern Metropolis (NM), located in the northwestern and northern parts of Hong Kong, has many planned mega-scale infrastructural developments in the coming few decades. This region is situated in a geologically complex sedimentary basin with intense faulting and deep weathering profile, and in particular complicated metamorphism. The presence of MS rocks has been posing challenges to the foundation design of some actively developing areas such as Yuen Long South, Kwu Tung North and San Tin Technopole. Due to the lack of geotechnical information for MS rocks, the prevailing foundation design guideline remains relatively conservative. With a view to reviewing the foundation design parameters of MS rocks, including the end-bearing capacity and the rock socket shaft resistance of piles, it is considered desirable to conduct trial piling works with full-scale instrumented pile loading tests at different sites underlain by meta-sedimentary rocks. Since 2024, the GEO initiated a large-scale pile loading test programme to collect essential information and test data with a view to exploring the feasibility to enhance the foundation design guidelines for MS rocks. In addition, the results of the pile load tests would directly be used in the foundation designs of site-specific projects, thus achieving productivity and saving in cost, time and sustainability.

In cognisance of recent successful applications of low-carbon GGBS concrete and high-strength S690 steel in building and infrastructural works, there is an opportunity to apply these new construction materials in foundation works. However, recent communications with relevant departments and practitioners revealed that there was generally a short of site operation and quality control experience with these new materials in piling works. It renders their applications in the construction of pile foundations not common in Hong Kong. As such, two large-diameter bored piles with high-percentage GGBS concrete (75% and 80% GGBS replacement of the

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total cementitious content) and two rock-socketed steel H-piles with high-strength S690 steel sections as well as high-percentage GGBS grout (75% GGBS replacement of the total cementitious content) are strategically designed in this study to address these concerns.

While the trial piling works are still actively on-going, this paper reports the preliminary findings of the above-mentioned study, highlighting the potential of enhancing the foundation design guidelines for MS rocks as well as the wider application of GGBS concrete/grout and S690 steel in piling works.

2 META-SEDIMENTARY ROCKS IN NORTHERN METROPOLIS

A considerable extent of the NM is underlain by MS rocks belonging to Lok Ma Chau Formation (Csl), with a minority belonging to Tuen Mun Formation (Ju) and Tai O Formation (Jo) (**Figure 2.1**). Both Lok Ma Chau Formation and Tuen Mun Formation are rather prominent at the northwest of New Territories. The rocks of Lok Ma Chau Formation occur as a northeast-trending outcrop and subcrop stretching from Tuen Mun to Lo Wu, comprising metamorphosed sandstone and carbonaceous siltstone with graphitic interbeds and calcareous content. While rocks of Tuen Mun Formation at NM are relatively confined to the area at the west and north of Tuen Mun, predominated by fine-grained, cross-bedded, well-graded quartzitic sandstone, metasiltstone and phyllite, the Tai O Formation at NM is exposed near the Ma Tso Lung area, including metasandstone, metasiltstone with graphite interbeds (Tse & Tang, 2024).

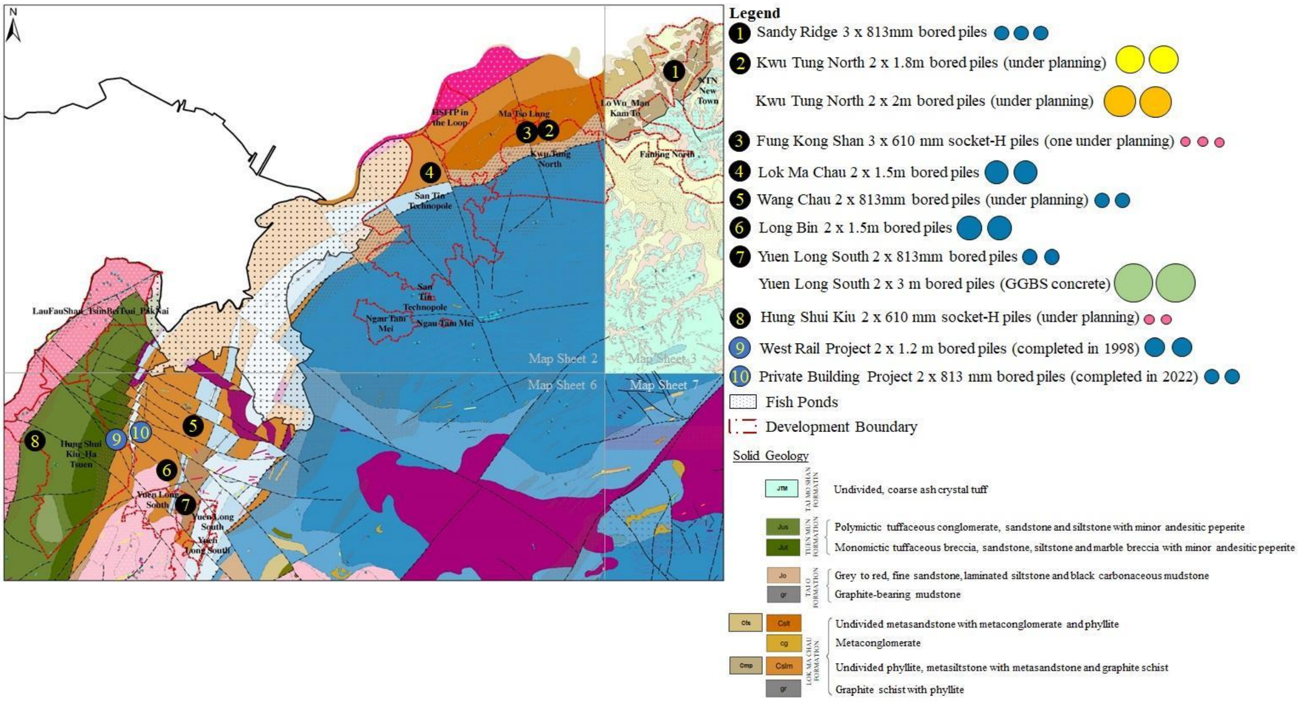

Figure 2.1: Overview of Geology at Northern Metropolis (Simplified from Tse & Tang, 2024) with locations of trial piles in this study

The engineering geological characteristic of MS rocks is complicated as the rock is sedimentary in nature and may have been subjected to different degree of metamorphism. The parent nature of MS rocks at NM is due to sedimentary process. The rock is mostly clastic, of which, the material strength and durability are largely controlled by the composition and property of the constituent grains as well as the degree of compaction and cementation. The bedding planes may also act as planes of weakness where weathering is more intense. As such, MS rocks could be consisting of various properties in lateral and vertical extent, and may change over short distances.

The sedimentary rocks subsequently subjected to dynamic metamorphism due to intense fault movements in the region. Langford et al. (1989) proposed that the structural framework of the northeast New Territories was dominated by the NE-trending Lo Wu-Tuen Mun Fold Belt (fault zone). The major structures have been updated as: the Deep Bay Fault, Yuen Tau Shan Fault, Mai Po Fault and the San Tin Fault in 2024 (**Figure 2.2**) (Tse & Tang, 2024).

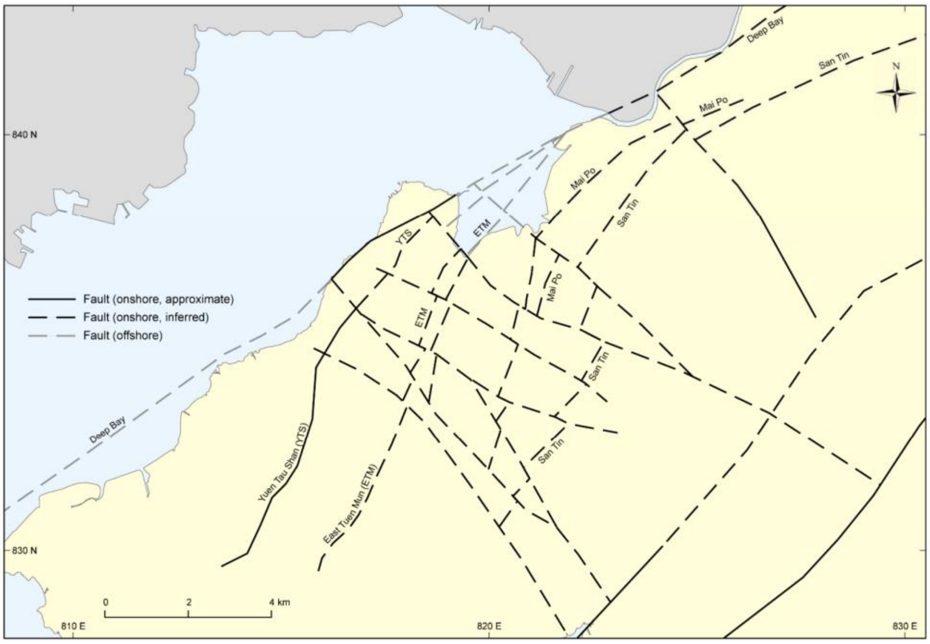

Figure 2.2: Major Faults in the Northwest New Territories
(Modified from Tse & Tang 2024 from So & Sewell 2019)

The tectonic movements may result in brecciated and brittled rocks, introducing further structures (i.e. joints and fractures) to the bedding planes originated from the sedimentary process. As a result, the engineering rockhead may not be as easily defined as compared to igneous rocks in Hong Kong. On the other hand, dynamic metamorphism is prominent in the northern and northwest of New Territories, particularly near San Tin Fault, by way of north or northwest inclined foliation (Sewell et al., 2000.). Foliation is favourable for weathering along the preferred alignment of minerals, leading to rapid disintegration of rock cores. Besides, local variations of foliation orientation will introduce anisotropic material properties relative to the alignment of the fabrics. In addition, other metamorphic processes such as recrystallization and hydrothermal alteration would lead to the rock strength varying across the rock mass depending on the type and distribution of the resulting minerals remain in the rock. For instance, if silicification takes place at bands intercalated with the metasedimentary rock, the rock strength may differ across the intercalated layers, with those layers possessing high concentration of silica may have a relatively higher strength than the adjacent layers.

For shallow foundation near the ground surface, the complicated engineering geological characteristic of MS rocks may have more pronounced effects to engineering works if they are exposed to air with time (e.g. Greenway et al., 1988). For deep pile foundations, the high confinement may have beneficial effects in minimising the adverse impacts of closely-spaced joints on end-bearing capacity of MS rocks. This aspect will be further reviewed based on the pile loading tests conducted in this study.

3 FOUNDATION DESIGN IN META-SEDIMENTARY ROCKS

In Hong Kong, pile foundation design in MS rocks primarily follows the Code of Practice for Foundation 2017 (2024 Edition) published by Buildings Department (BD) (BD, 2024) with the presumed design values summarized in **Table 3.1**. It should be noted that the design provision for Category 2 rock (i.e. MS rocks) first appeared in the 2017 Code. With the lack of geotechnical information for MS rocks at that time, a presumed allowable bearing pressure of 3,000 kPa was conservatively set. This design value is akin to that used for Category 1(d) rock i.e. Grade III or better granite or volcanic rock with not less than 50% Total Core Recovery of the designated grade. Before 2017, some housing projects might adopt a presumed allowable bearing pressure of 5,000 kPa in their foundation designs i.e. akin to Category 1(c) rock.

Table 3.1: Presumed allowable vertical bearing pressure extracted from BD (2024)

Category	Description of rock or soil	Presumed allowable bearing pressure (kPa)	Presumed allowable bond or friction (kPa)
2	*Meta-Sedimentary rock:* Moderately decomposed, moderately strong to moderately weak meta-sedimentary rock of material weathering grade III or better, and with not less than 85% TCR of the designated grade.	3,000	300 (under compression or transient tension) 150 (under permanent tension)

Instead of adopting the presumed value for foundation design in MS rocks, there are several projects involving the use of Rock Mass Rating (RMR) (GEO, 2006), coupled with site-specific pile loading tests, to determine the allowable bearing pressures of MS rocks for the projects. For example, Yau & Lau (2024) carried out two pile loading tests on MS rocks at Kiu Cheong Road, Tin Shui Wai and by using the RMR method, they obtained the consent from BD to adopt an allowable bearing capacity of 5,000 kPa in the foundation design leading to cost and time saving of the piling works for a building project.

The use of pile loading tests to enhance foundation design was also reported by Littlechild et al. (2000). They carried out two pile loading tests on MS rocks and found that the mobilised bearing pressure could be up to 26,500 kPa and 24,000 kPa respectively. Together with a series of pile loading tests on other rock types, the local railway project adopted an allowable bearing capacity of at least 7,500 kPa for MS rocks and others.

4 PLANNING OF TRIAL PILING WORKS IN THIS STUDY

Based on a review of the local foundation design experience in MS rocks, there is room for enhancing the prevailing design guideline for MS rocks. The use of full-scale pile loading tests appears to be a promising approach to investigate the actual pile-rock behavior under pressure (e.g. Littlechild et al., 2000). As the MS rocks in the NM may have varying properties in terms of rock strength, fractureness, presence of foliation or bedding plane, etc., it is planned to carry out a systematic pile load test programme targeting on MS rocks of different characteristics in the NM. **Table 4.1** summarises the pile loading tests conducted in this study as well as the brief details of trial piles, testing systems and ground conditions. The locations of test sites are shown in **Figure 2.1**.

Table 4.1: Summary of trial piles conducted in this study

Site	Pile No.	Pile Diameter (mm)	Rock Socket Diameter (mm)	Pile Length (m)	Rock Socket Length (m)	Pile Founding Material *	Pile Type / Loading System
Yuen Long South	YLS-P1	813	750	47.17	1.61	SD Meta-siltstone / SD Meta-sandstone	Bored Pile / 10MN O-cell with kentledge
Yuen Long South	YLS-P2	813	750	46.92	0.9	SD Calcareous Meta-siltstone	Bored Pile / 10MN O-cell with kentledge
Yuen Long South	GGBS-YLS-P1	3000	2850	63	0.3	-	For studying GGBS, not pile loading test
Yuen Long South	GGBS-YLS-P2	3000	2850	52	0.3	-	For studying GGBS, not pile loading test
Long Bin	LB-P1	1500	1350	90.86	1.5	SD / MD Meta-siltstone	Bored Pile / 32MN O-cell with kentledge
Long Bin	LB-P2	1500	1350	74.07	1.5	SD/ MD / HD Meta-siltstone	Bored Pile / 32MN O-cell with kentledge

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Site	Pile No.	Pile Diameter (mm)	Rock Socket Diameter (mm)	Pile Length (m)	Rock Socket Length (m)	Pile Founding Material *	Pile Type / Loading System
Sandy Ridge	SR-P01	813	750	28.09	3.8	SD/ MD Meta-siltstone	Bored Pile / 10MN O-cell without kentledge
Sandy Ridge	SR-P02	813	750	25.57	3.1	SD/ MD Meta-siltstone	Bored Pile / 10MN O-cell without kentledge
Sandy Ridge	SR-P03	813	750	40.1	4.17	SD/ MD Meta-sandstone	Bored Pile / 10MN O-cell without kentledge
Lok Ma Chau	LMC-P1	1500	1350	39.6	1.8	SD Calcareous Meta-siltstone	Bored Pile / 32MN O-cell with kentledge
Lok Ma Chau	LMC-P2	1500	1350	43.94	1.59	SD Calcareous Meta-siltstone	Bored Pile / 32MN O-cell with kentledge
Fung Kong Shan	FKS-P1	610	550	54.21	2.2	MD Meta-siltstone	Socketed-H with S690 steel section / 6MN O-cell without kentledge
Fung Kong Shan	FKS-P2	610	550	36.95	6.4	SD Meta-siltstone (along rock socket)	Socketed-H with S690 steel section / top load with kentledge

* SD stands for slightly decomposed, MD stands for moderately decomposed, HD stands for highly decomposed, CD stands for completely decomposed according to the rock descriptions in Geoguide 3

So far, loading tests on 11 trial piles at five sites straddling across NM have been completed. Data interpretation and analysis are on-going. Amongst them, nine are rock-socketed bored piles (813 mm or 1.5 m in diameter) whilst two are rock-socketed H-piles (610 mm in diameter) aiming also for studying the use of S690 steel section and high-percentage GGBS grout. Two additional trial piles are rock-socketed bored piles (3 m in diameter) constructed using high-percentage GGBS concrete without any loading tests. The founding level of piles are determined by predrills. In general, for tests with both O-cell and kentledge, shorter rock socket length (i.e. 0.9 m to 1.8 m) is adopted, which targeted to test the ultimate rock socket friction. For tests with O-cell but without kentledge, as the reaction to the O-cell is solely provided by rock socket and the soil shaft above, longer rock socket length (i.e. 2.2 m to 4.17 m) is adopted to ensure sufficient reaction is provided to the O-cell for applying load to the bearing stratum.

Apart from the pile loading tests, a series of pre-drilling works, post-drilling works, field tests in boreholes, laboratory tests on rock specimens and geophysical survey have been carefully planned to obtain information to support the study. For example, in view that MS rocks are usually highly fractured, rendering conventional uniaxial compressive strength test and diametric point load test difficult to carry out, it is planned to study the feasibility of using irregular lump point load tests to replace point load test to determine the strength of MS rocks. This will require an establishment of the correlation between uniaxial compression tests and irregular lump point load tests. In addition, in-situ Goodman Jack test and laboratory tests will be carried out, where applicable, to assess the rock modulus, which is an important property dictating the pile settlement behavior. These ground investigation works and laboratory tests are being conducted and the results will be reported later.

5 PILE LOADING TEST SETUP AND PRELIMINARY FINDINGS

5.1 Pile Loading Test Setup and Instrumentations

Figure 5.1 shows the schematic sectional views for all the trial piles conducted in this study. As illustrated, a majority of the pile loading tests is conducted using the bi-directional loading system, namely the Osterberg cell (O-cell) installed at the pile base. Comparing to conventional top loaded pile loading tests with kentledge, O-cell directly exerts loading on the bearing rock and measured the actual pressure applied to the bearing strata. Another benefit of loading at the pile base is to allow measurement of rock socket friction together with the end bearing pressure at the same time. This setup well overcomes the limitation of the conventional top loading system using kentledge of which the load applied at the top of pile will dissipate along the soil portion (even with sleeving) and the forces being mobilised along the rock sockets and on the pile bases have to be back-calculated (i.e. indirectly) from strain gauges readings. In this study, all piles above the tested rock socket sections are sleeved by permanent casing with bituminous coating. Kentledge on the ground surface would be added if additional reaction force is required for the sake of maximising the end-bearing pressure on rock.

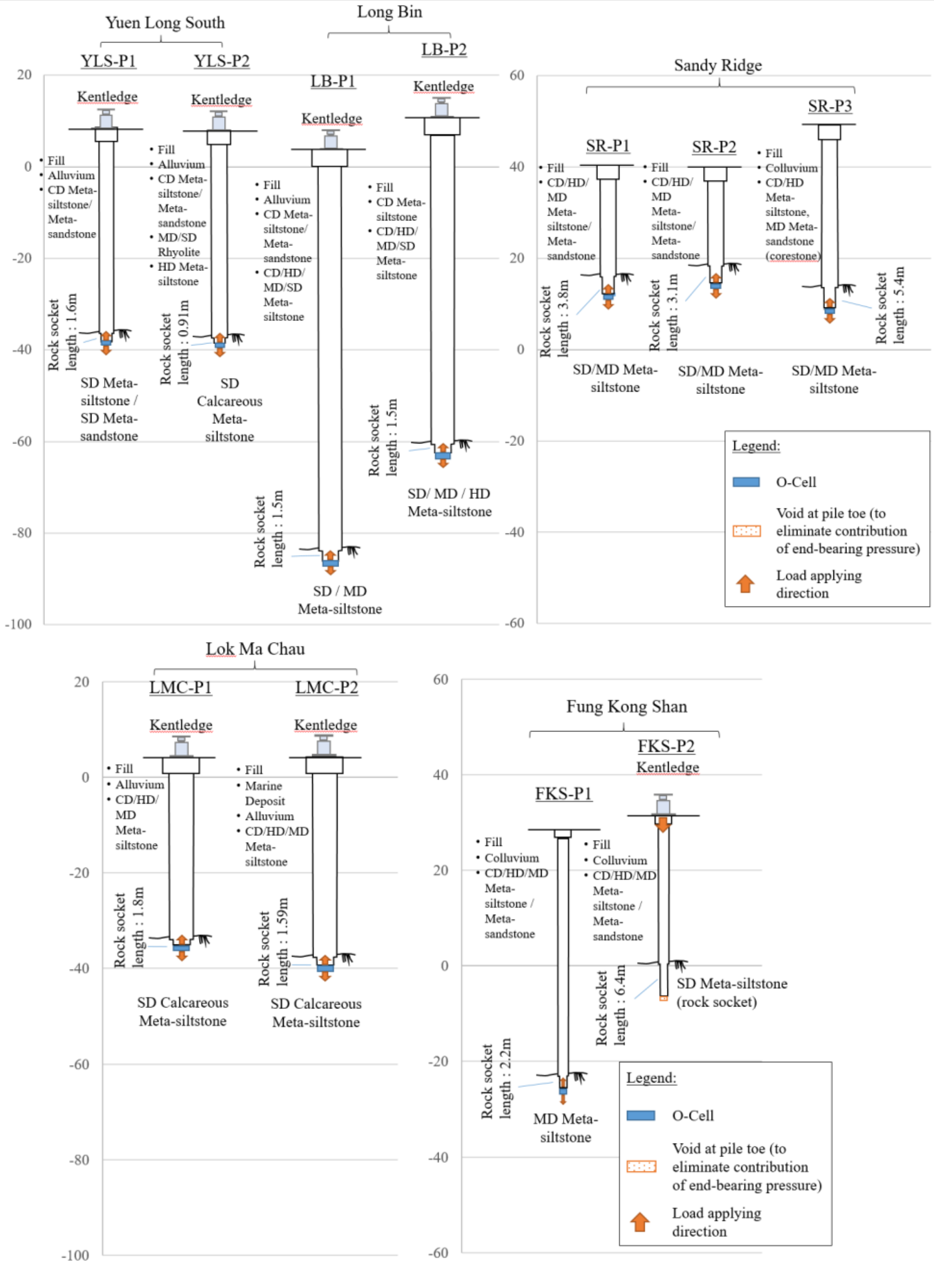

Figure 5.1: Schematic sectional views of trial piles

All trial piles are heavily instrumented (see **Figure 5.2**). The measurement of movement at different parts of the pile is critical. A series of extensometers are installed at the top and bottom plates of O-cell, rockhead level and pile top, aiming to measure the gross movement and shortening of the pile. A set of linear vibrating wire displacement transducers (LVWDT) is installed between the top and bottom plates of the O-cell, aiming to measure the stroke of O-cell thereby cross-checking whether its opening has reached the limit.

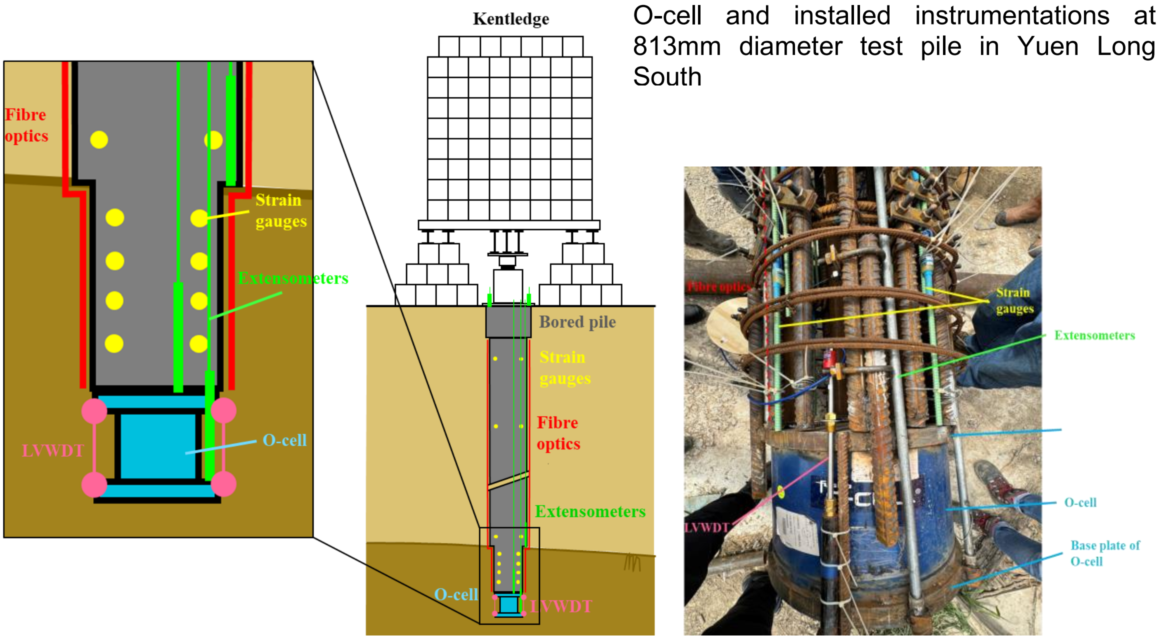

Figure 5.2: Illustration of bi-directional loading system with O-cell and instrumentation arrangement

For force measurement, an innovative dual strain measurement scheme is adopted where the forces mobilised along the pile shaft are concurrently captured by both strain gauges and fibre optics. The measured strain (ε) along the piles can be converted to pile axial force (Q) at the strain gauge level by multiplying the axial pile stiffness EA, where E is the pile modulus and A is the pile cross-section area. Apart from point-wise measurements by the strain gauges, fibre optics provide a continuous profile of strain measurement results making up the missing data between individual strain gauges. Fibre optic, which gives a continuous load distribution profile, is particularly useful in small diameter piles as there is limitation on the number of strain gauges that could be installed under a congested environment. For more details about the test setup, instrumentation arrangement and loading schedules adopted in this study, please refer to Lam et al. (2025).

5.2 Preliminary Results

While the analysis of test data is ongoing, preliminary results of two selected trial piles from test sites at Yuen Long South and Long Bin in this study are presented in **Table 5.1**, together with four existing pile loading tests for MS rocks available from the literature. Echoing from section 2 above, MS rock has much affected by foliation and possibly preserved bedding, which makes the rock generally more fractured than granitic rock and volcanic rock. Therefore, the 'Fracture State' of the founding rock mass is also summarised in the table, in terms of Total Core Recovery (TCR), Rock Quality Designation (RQD) and Fracture Index (FI) (Geoguide 3). In addition, Rock Mass Rating (RMR) (Bieniawski, 1989) for each test pile is interpreted from the respective borehole log in accordance with GEO Publication No. 1/2006. RMR, which includes parameters on rock strength, RQD, conditions of joints, etc., is also a widely used index to classify rock mass. It could be used for estimating the in-situ deformability of rock mass (Bieniawski, 1993), which is useful for estimating the settlement of the foundation.

From **Table 5.1**, albeit involving only two out of five sites under this study and two sites from the literature, all piles have achieved the designed test load with a settlement at pile toe less than 1.2% pile base diameter, mobilising end-bearing pressure of about 16,000 kPa to 27,000 kPa. It is noteworthy that the maximum test load was capped by the testing equipment's capacity.

Table 5.1: Preliminary results of selected pile loading tests in this study and other results of MS rocks in Hong Kong

Site	Pile No.	Pile Type	Pile Diameter (mm)	Rock Socket Diameter (mm)	Mobilised End Bearing Pressure (kPa)	Pile Base Settlement (mm)	Pile Founding Material	TCR / RQD / FI (within 1B) #	RMR At Bearing Stratum
Yuen Long South **(this study)**	YLS-P1	Bored Pile	813	750	~27,000	~4 (0.5% dia.)	SD Meta-siltstone / SD Meta-sandstone	100/ 100/ 0	84
Long Bin **(this study)**	LB-P1	Bored Pile	1500	1350	~25,000	~12 (0.9% dia.)	SD / MD Meta-siltstone	100/ 0-16/ 14.1 - >20	47
West Rail [1]	TSW1	Bored Pile	1200	1200	26,530	14 (1.2% dia.)	SD meta-sandstone	-/ 43-77/ -	59 [3]
West Rail [1]	TSW2	Bored Pile	1200	1200	24,000	2 (0.17% dia.)	SD meta-siltstone	-/ 86-88/ -	58 [3]
Kiu Cheong Road [2]	BTP-01	Bored Pile	813	813	16,254	9.4 (1.2% dia.)	Meta-sandstone	93 (min)/ 13/ >20 [4]	53 [4]
Kiu Cheong Road [2]									52 [4]

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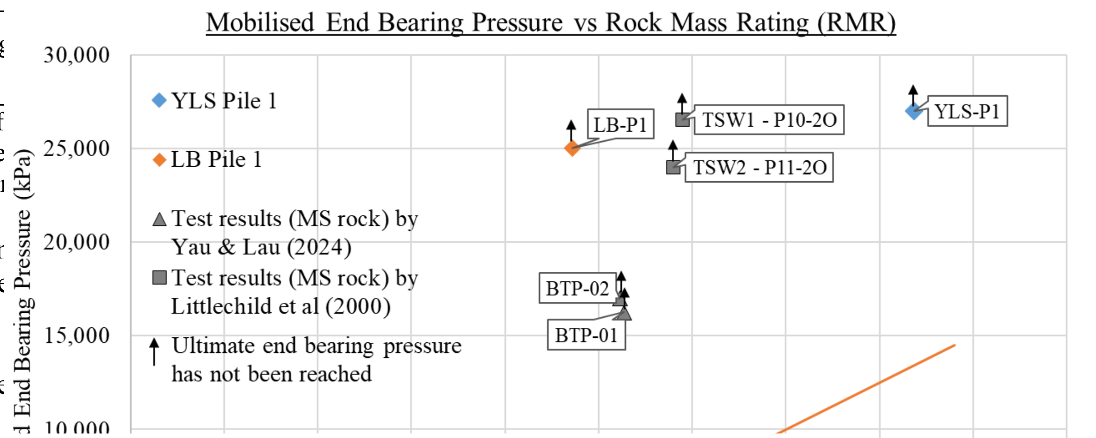

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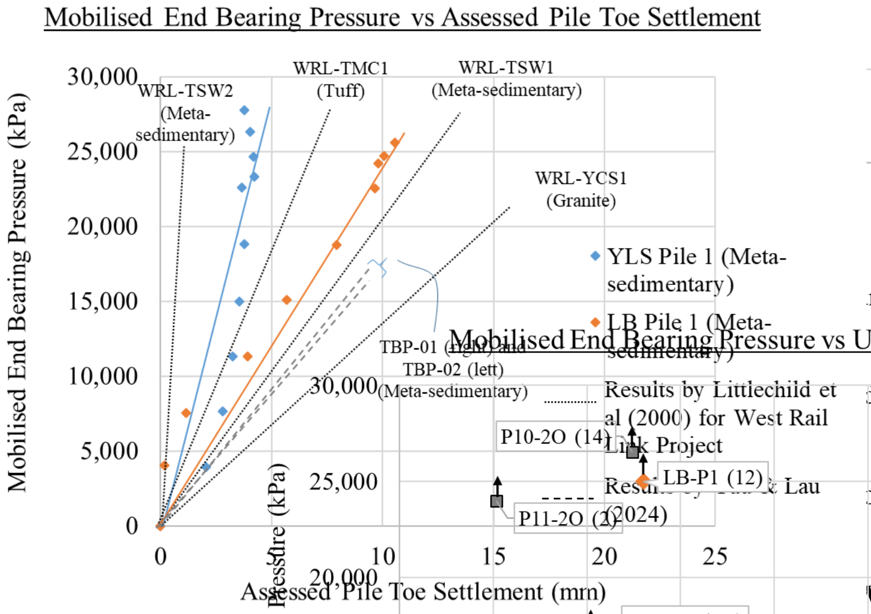

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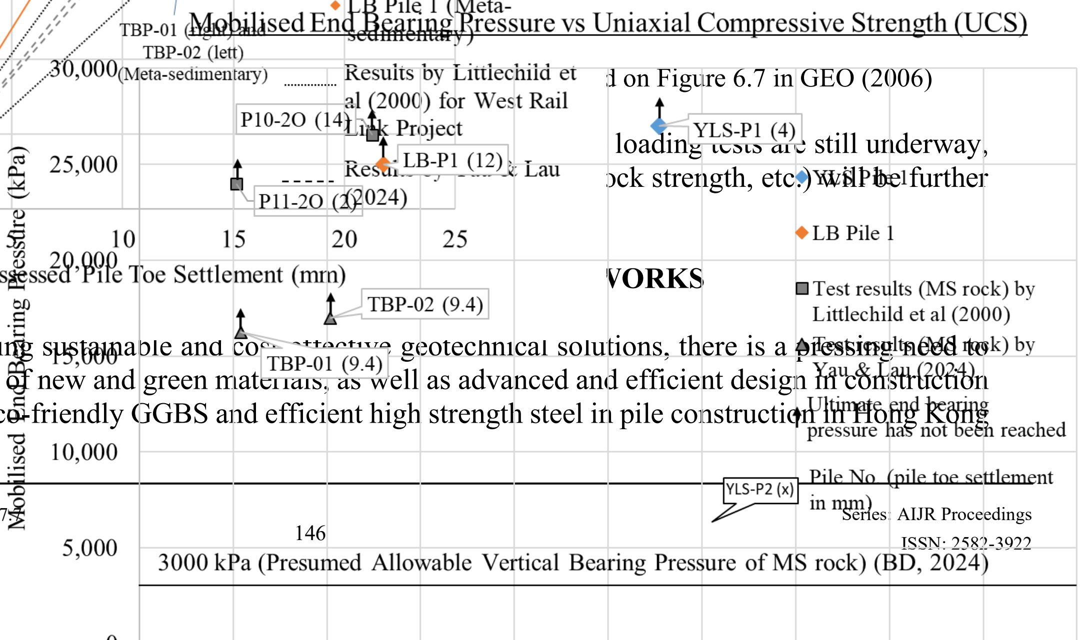

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With a view to advancing sustainable and co... effective geotechnical solutions, there is a pressing need to promote wider application of new and green materials, as well as advanced and efficient design in construction works. While the use of eco-friendly GGBS and efficient high strength steel in pile construction in Hong Kong is still at the early stage, technical design considerations and industry's concerns on constructability remain challenges to be addressed. In connection with the systematic pile load tests conducted by the GEO in the Northern New Territories, concrete with high replacement level of GGBS as the supplementary cementitious material (SCM) and high strength S690 steel H-sections were used in some selected piles. These results will not only optimise the foundation design for MS rocks in the Northern Metropolis areas, but will also provide technical evidence to support broader adoption of GGBS concrete and high strength S690 steel in foundation projects.

6.1 Trial Piles with High Percentage GGBS at Yuen Long South

Benefits and Challenges

The use of GGBS, a by-product of the iron manufacturing industry and has been used as a SCM in concrete, has been proven effective in reducing the total carbon emission of the concrete production process by lowering the content of Ordinary Portland Cement (OPC). Since the publication of the General Specification for Civil Engineering Works (GS) in 2012, GGBS concrete (with a replacement level between 35% and 75% allowed for normal concrete) has been used in the construction of superstructure and precast facades, but rarely seen in the construction of piles in Hong Kong. It is probably because of various practical concerns from the stakeholders, including piling contractors and concrete suppliers, of adopting GGBS concrete with a high replacement level (i.e. ≥ 50%) in piling works, such as potential high cohesiveness of the concrete due to the fineness of GGBS, which could pose challenges to the tremie concreting process and the pile casing extraction process. Other concerns include workability, retention of slump, temperature evolution in the pile, and the long-term strength development.

Technical Details, Testing and Monitoring of the Trial Piles

In order to collect more field data and site operation observations of using high percentage GGBS concrete in the actual construction operation and quality control of piling works with large concreting volume and long concreting time on site, two full-scale trial bored piles of 3 m in diameter, namely GGBS-YLS-P1 and GGBS-YLS-P2 with 75% and 80% (i.e. exceeded the recommended replacement % in the GS) of GGBS replacement level respectively, were constructed at a site in Yuen Long South (see **Figure 6.1**).

Technical details	GGBS-YLS-P1	GGBS-YLS-P2
Pile shaft diameter	3.0 m (2.85 m in rock)	3.0 m (2.85 m in rock)
Pile shaft length	63 m (300 mm toe-in into rock)	52 m (300 mm toe-in into rock)
Steel reinforcement ratio	1.8% to 2.6%	1.8% to 2.6%
Proportion of GGBS to total cementitious content in concrete	75%	80%
Concrete grade strength	60D/20	60D/20
Designed slump value	200 mm	200 mm

Figure 6.1: Overview of the trial piling works

To properly identify any potential construction issues during site operation and quality control, the entire construction process, including tremie concreting and pile casing extraction, was carefully monitored and recorded. Typical testing and monitoring procedures for bored piles, including slump retention test for the workability, sonic logging test and interface core drilling were applied. In addition, concrete cubes for compressive strength tests at the age from 3 days to 90 days were sampled, together with full-length core drilling for UCS tests at the age from 58 days to 120 days were carried out for capturing the strength development from early age to long term. To address the industry's concern about the temperature evolution in the pile, beside conventional thermal couples, fibre optic sensors (for continuous temperature-change profile) were also installed along the pile shaft and across pile diameter.

Results and Observations

One of the major concerns of using GGBS concrete in piling works is the high cohesiveness of the GGBS concrete with a high replacement level. In comparing with typical concreting time of a bored pile with Pulverised Fly Ash (PFA) concrete, a longer pouring time of concrete from the concrete bucket to the tremie pipe was observed when a high percentage of GGBS was adopted. As reflected by the contractors and the concrete supplier, other concreting stages (e.g. concrete pouring from the mixing plant to the agitator of trucks at the plant, and the transfer from the agitator of trucks to the concrete bucket at the site) could have also taken a slightly longer time due to the cohesiveness of GGBS concrete, especially at the early stage of the construction works due to a lack of experience with the new concrete mix. As experience accrued in optimising the concrete design mix and concreting procedure, the situation was found to be improved.

Other aspects of the construction process for both trial piles were found to be normal. Despite the relatively higher cohesiveness of the GGBS concrete, no clogging of the tremie pipe was observed. There was also no difficulty during pile casing extraction. As reported by the piling contractor, comparing with the typical operation when OPC or PFA concrete was used, no extra power was required to extract the casing, and no up-dragging of the steel cage was observed throughout the process. For workability, the measured average slumps for both trial piles fulfilled the design requirements. Strength development was observed slower at the early stage with increasing replacement level of GGBS. However, the 28-day strength for both 75% and 80% GGBS concrete met the design requirements. The UCS tests on concrete cores extracted from the test piles at the age from 58 days to 120 days indicated that there was a continuous strength gain of GGBS concrete with time. More technical details about these trial piles can be referred to Chiu & Sze (2024).

6.2 Trial Piles with High Strength S690 Steel H-section at Fung Kong Shan

Benefits and Challenges

Due to its higher design structural capacity, high strength steel attracts industrial attention due to benefits of reduction in steel tonnages and structural weights, and saving in cost. Following the successful application of high strength S690 steel in the construction of the Cross Bay Link, the industry has been exploring to extend its application to other construction disciplines, including piling construction. Under the current foundation design standard, however, effective adoption of high strength S690 steel could also be governed by geotechnical capacity which errs on the conservative side. Long socket length (over 10 m) for achieving the currently required shaft friction leads to heavy machinery and high construction cost. Limited experience for welding high strength S690 steel on site in Hong Kong also imposes hurdle for wider application.

Technical Details and Observations during the Construction of the Trial Piles

Two full scale trial socketed H-pile of 610 mm in diameter, namely SHP-FK-P1 and SHP-FS-P2, using high strength S690 steel H-section and 75% GGBS grout were constructed at one of the test sites in this study, namely Fung Kong Shan near Kwu Tung North. In order to verify the end-bearing capacity and the rock socket shaft resistance of piles in meta-sedimentary rocks beneath the site, an O-cell was installed at the bottom of SHP-FK-P1 and a kentledge system was constructed at the top of SHP-FK-P2 for pile loading test. The technical details of these two trial piles are summarised in **Table 6.2**.

Table 6.2: Technical details of trial piles with S690 steel and GGBS grout

	SHP-FK-P1 (with Osterberg cell)	**SHP-FK -P2 (with kentledge)**
Pile shaft diameter	610 mm (550 mm in rock)	610 mm (550 mm in rock)

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Steel H-section	305×305×219 JBP (S690)	305×305×219 JBP (S690)
Pile shaft length	54 m (2.2 m socket into rock)	37 m (6.4 m socket into rock)
Proportion of GGBS to total cementitious content in grout	75%	75%
Grout strength	30 MPa	30 MPa

Figure 6.2 shows some photos during the construction of the trial piles. The high strength S690 steel H-sections were fabricated by welding three steel plates in factory. Shear studs were installed along the H-sections to maximise the bonding at the steel-grout interface. Fibre optic sensors and strain gauges were also installed along the H-sections for monitoring the strain development and pile movement throughout the load test. While strain gauges provide point-wise strain measurements at the installation levels, the fibre optic sensors adopting Optical Frequency-domain Reflectometry (OFDR) technique pick up high spatial resolution of continuous strain data which facilitates determination the shaft friction along the pile.

(a) (b) (c)

Figure 6.2: Construction details of trial piles with high strength S690 steel H-section: (a) Instrumentation with fibre optic sensors; (b) on-site welding; and (c) testing of weld.

These trial piles also aim to demonstrate the constructability of high strength S690 steel in piling construction, including the installation of steel H-sections and on-site welding operation. Qualified high strength S690 steel welders were trained in advance and engaged in the welding process. Hold time before weld tests and inspection procedures using non-destructive testing methods (including Magnetic Particle Inspection and Ultrasonic Examination), in accordance with the current steel design standard, were strictly followed to identify any potential challenge in the construction and quality control. The welding process was reported smooth during the construction and no prolongation was recorded comparing to construction using typical steel H-section. While the detailed interpretation of the pile load test results was still undergoing, preliminary results revealed that the end-bearing capacity and the rock socket shaft resistance tested were well above the values in the current foundation standard.

7 CONCLUSING REMARKS AND WAY FORWARD

A comprehensive trial piling works programme is being implemented at different sites within NM. All trial piles are founded on MS rocks with varying characteristics (e.g. different RMR values). Based on the preliminary results of pile loading tests conducted at Yuen Long South and Long Bin together with some existing local test data, there is a room for enhancing the prevailing foundation design guideline for MS rocks i.e. the presumed allowable bearing pressure and the presumed allowable bond or friction in rock socket for MS rocks in the Northern New Territories. Taking cognisance of the variable nature of MS rocks, and subject to the findings of other pile loading tests and the associated field and laboratory testing results of which the data interpretation and analysis are underway, it is considered promising that the foundation design guidelines for

MS rocks could be improved. Such improvement could bring about substantial saving in cost and time of the foundation works whilst benefiting material saving and sustainability in general. In fact, results of some pile loading tests conducted in this study have been adopted by the site-specific housing development projects for improving their foundation designs. It signifies the immediate benefits brought about by this study.

The successful application of high-percentage GGBS in both concrete (75% and 80% replacement) and grout (75% replacement) in the trial piles have addressed the industry concerns regarding constructability and operational challenges of this eco-friendly materials in piling works. In a similar fashion, the trial piles using high-strength S690 steel H-sections in socketed piles have well demonstrated viable constructability, including welding and installation processes, while achieving robust shaft resistance and end-bearing performance. These innovations align with sustainability goals by reducing carbon emissions and material usage.

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