Review on the End Bearing Capacity of Large Diameter Bored Piles founded on Meta-sedimentary Rock in Hong Kong

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ABSTRACT

The HKSAR Government has introduced the Northern Metropolis Development Strategy to transform the northern part of Hong Kong into a metropolitan area for living, working, and traveling. Covering 30,000 hectares, it includes districts like Yuen Long, Tin Shui Wai, Fanling, and Sheung Shui. The strategy aims to increase land availability, improve transport infrastructure, and develop housing, industries, and community facilities. The government has prioritized the Northern Metropolis in its strategic development plans, emphasizing an "industry-driven and infrastructure-led" approach to integrate it with the nation's overall development. Meta-sedimentary bedrock formations are not uncommon in the Northern Metropolis. A review of the allowable end bearing capacity of this bedrock has been conducted in this paper. The Code of Practice for Foundation 2017 specifies the allowable end bearing capacities for various types of rocks and soils in Hong Kong. For Grade III meta-sedimentary rock, it is limited to 3,000kPa, while for granitic and volcanic bedrock, it has been upgraded to 7,500kPa. To study the behaviour of piles founded on Grade III meta-sedimentary rock, two bored piles were tested each under a load three times the design working load. The test results showed maximum mobilized end bearing pressures exceeds 15,000kPa (i.e. with a factor of safety of 3, the allowable bearing pressure is greater than 5,000kPa). These findings provide valuable insights into pile behavior on meta-sedimentary rock in the Northern Metropolis, suggesting efficient and economical foundation design can be achievable in the new development areas.

Keywords: Allowable bearing pressure, Meta-sedimentary rock, Rock Mass Rating

INTRODUCTION

The HKSAR Government introduced the Northern Metropolis Development Strategy in 2021 to transform the northern part of Hong Kong into a metropolitan area for living, working, and traveling. Covering 30,000 hectares, it includes the Yuen Long and North districts, with existing new towns like Yuen Long, Tin Shui Wai, Fanling, and Sheung Shui. The strategy aims to increase land availability, improve transport infrastructure, and develop housing, industries, and community facilities.

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The government has prioritized the Northern Metropolis (NM) in its strategic development plans, as highlighted in the 2022 Policy Address. It is envisioned as a new engine for Hong Kong's growth, with an "industry-driven and infrastructure-led" approach emphasized in the 2023 Policy Address to integrate it with the overall development of the country.

Meta-sedimentary rocks are not uncommon in NM. GEO provides a distribution map of Paleozoic rocks (see Figure 1). Late Paleozoic rocks include sedimentary rocks of the Devonian, Carboniferous, and Permian periods, which are distributed in the northern and western parts of Hong Kong. Some of these rocks have undergone thermal and dynamic metamorphism.

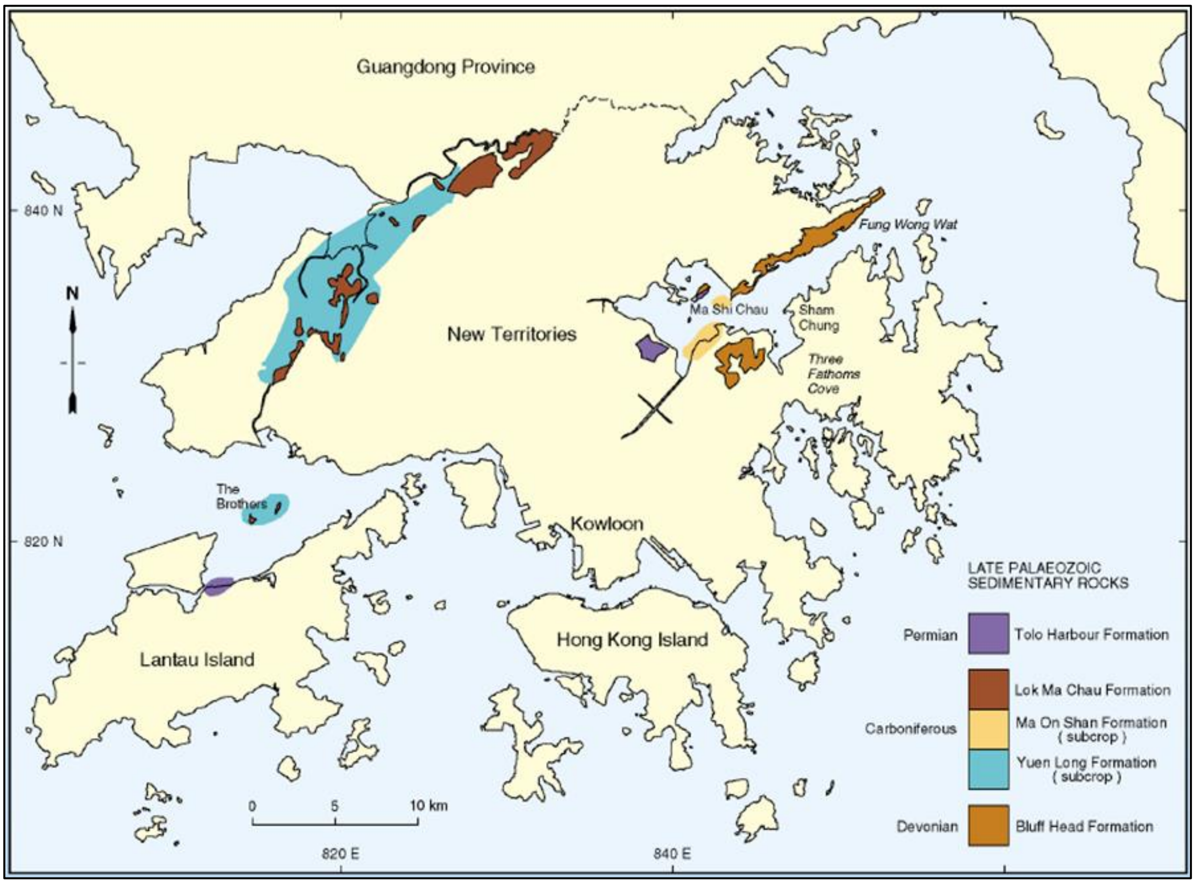

Figure 1 – Distribution of Late Paleozoic sedimentary rocks in Hong Kong

Large scale development will be scheduled in the coming decade in NM. Foundation works would be the first step for the development. In the current practice, the allowable end bearing pressure of meta-sediment rock for design is significantly lower than that of Granitic or Volcanic rock.

To achieve cost-effective developments in NM, it is necessary to review the allowable end bearing pressure of meta-sedimentary rock. To this end, the authors have carried out load tests on two large diameter bored piles founded on grade III meta-sedimentary rock in Kiu Cheong Road, Tin Shui Wai with an objective to verify that meta-sedimentary rock can provide an allowable bearing capacity of 5,000kPa under the fulfillment of rock strength [(Uniaxial Compressive Strength (UCS) or an equivalent Point Load Index Strength (PLI_{50})] and Total Core Recovery (TCR) not inferior than that of granitic or volcanic rock with the same allowable bearing capacity.

In addition, references have also been made to Hill et al (2000) who have reviewed the allowable bearing pressure of rocks for founding of piles in 14 number of pile loading tests conducted for the West Rail Project Phase 1, together with some 20 numbers of full scale loading tests on piles and barrettes in late 1990s. The rocks under Hill's review included also meta-sedimentary rock.

CURRENT DESIGN PRACTICE

Wong (2014) reviewed the development of presumed bearing pressure of granitic and volcanic rock for foundation design in Hong Kong. The foundation design in Hong Kong follows the Code of Practice for Foundation (CoPF) 2017 by the Buildings Department of HKSAR. The allowable bearing pressure (q_a) for pile design is determined based on the categories of rocks. The presumed allowable bearing pressure (qa) for pile design is extracted from Table 2.1 of CoPF 2017 is shown in Table 1 below.

Table 1: Presumed Allowable Bearing Capacity for Foundations (BD, 2017)

Category	**Description of rock**	**q_a (kPa)**
1(a)	Grade II or better granite/volcanic rock, TCR of the designated grade = 100%, UCS≥75MPa/PLI_{50}≥3MPa	10,000
1(b)	Grade II or better granite/volcanic rock, TCR of the designated grade ≥ 95%, UCS≥50MPa/PLI_{50}≥2MPa	7,500
1(c)	Grade III or better granite/volcanic rock, TCR of the designated grade ≥ 85%, UCS≥25MPa/PLI50≥1MPa	5,000
1(d)	Grade III or better granite/volcanic rock, TCR of the designated grade ≥ 50%	3,000
2	Grade III or better meta-sedimentary rock, TCR of the designated grade ≥ 85%	3,000

In 2023, Geotechnical Engineering Office (GEO) published a TGN No. 53 which recommends to increase the presumed allowable end bearing pressures of rocks for public works projects (GEO, 2023). The recommendation is now also generally acceptable for private development projects. The updated allowable end bearing pressures are shown in Table 2 below:

Table 2: Presumed Allowable Bearing Capacity for Foundations (GEO, 2023)

Category	**Description of rock**	**q_a (kPa)**
1(a)	Grade II or better granite/volcanic rock, TCR of the designated grade = 100%, UCS≥75MPa/PLI_{50}≥3MPa	12,500
1(b)	Grade II or better granite/volcanic rock, TCR of the designated grade ≥ 95%, UCS≥50MPa/PLI_{50}≥2MPa	10,000
1(c)	Grade III or better granite/volcanic rock, TCR of the designated grade ≥ 85%, UCS≥25MPa/PLI50≥1MPa	7,500
1(d)	Grade III or better granite/volcanic rock, TCR of the designated grade ≥ 50%	3,000
2	Grade III or better meta-sedimentary rock, TCR of the designated grade ≥ 85%	3,000

The TGN has recently revised the presumed allowable bearing capacity of igneous rocks, increasing it from 5,000kPa to 7,500kPa after careful review of past experiences. However, it is crucial to highlight that the presumed allowable bearing pressure for meta-sedimentary rock, as specified in both the CoPF and TGN, has not included the material strength of the rock (UCS/PLT_{50}) as a criterion. Instead, it remains limited to 3,000kPa depending only on rock grade and TCR, which is considered a conservative value.

One of the authors of this study has participated in the West Rail Pile Load Test Programme in the late 1990s, where two instrumented bored piles were subjected to maximum bearing pressures of 25MPa in the Tin Shui Wai Area, specifically on meta-sedimentary rock. The authors believes that the ultimate bearing pressure of the rock is largely dependent on its strength of bearing rock and suggests that the current allowable bearing pressure of 3,000kPa is overly conservative. The authors emphasizes the need for a review of this value based on the availability of more test data.

With the aim of achieving a cost-effective design for a project in Kiu Cheong Road, Tin Shui Wai, the authors have conducted static load tests on piles founded on meta-sandstone. Two instrumented bored piles with a diameter of 813mm were tested at the Kiu Cheong Road site to validate the design assumption of 5,000kPa for meta-sedimentary rocks (Grade III or above with UCS≥25MPa or PLI_{50} ≥1MPa).

LOAD TEST

Ground Conditions of the Site

The site-specific ground investigation reveals that the site is underlain by the superficial deposits typically consist of fill, occasionally with pond deposit, alluvium, and highly to completely decomposed meta-sandstone and meta-siltstone. Underlying these deposits is moderately to slightly decomposed meta-sandstone and meta-siltstone. The founding bed rock is categorized as Category 2 rock in Table 2.1 of CoPF 2017. The Category (2) bedrock level, which is defined as at least 5m of Grade III or better Rock with Total Core Recovery not less than 85%, varies between -19.8mPD at southern of the site and -48.72mPD at northern of the site respectively. Point load test (PLI50) and uniaxial compression strength (UCS) test were carried out on selected rock core samples retrieved from boreholes during GI stage. The results indicated that the point load index strength PLI50 for meta-sedimentary rock (siltstone/sandstone) ranged from 1.2MPa to 9.9MPa.

Details of the test piles

The authors used the Rock Mass Rating (RMR) method developed by Bieniawski (1974) and Bieniawski (1989) to verify the allowable bearing pressure of the bedrock. Referring to GEO publication No. 1/2006, RMR 50 was adopted as the bearing stratum with an allowable bearing pressure of 5,000kPa. The authors analyzed the borehole logs using RMR and concluded that the two boreholes BH15 and BH22 showed the weakest condition among the 34 boreholes conducted on site. Therefore, two trial piles were conducted at the locations of BH15 and BH22.

Two 813 diameter bored piles were tested to determine the mobilized bearing pressure of under static load. The details of the test piles are shown in Table 3 below.

Table 3: Details of Test Piles

Trial Pile No.	**Reference Boreholes**	**Pile Head Level (mPD)**	**Founding Level (mPD)**	**Pile Length (m)**	**Min. TCR within 3B# below Pile base**	**Bottom Level of Sleeve Casing (mPD)**
BTP-01	BH15	+4.02	-46.34	50.36	93%	-46.34
BTP-02	BH22	+3.92	-29.96	33.88	90%	-29.96

Note: #B is the diameter of pile base

The two 813mm diameter bored piles instrumented with strain gauges (Plate 1) and extensometers were tested to determine the end bearing capacity of meta-sedimentary bedrock. Strain gauges were installed at 8m c/c interval that were used to measure the change in strain along pile shaft and pile base which could estimate the load developed along pile shaft during load testing. The extensometers were aimed at measuring the base movement during load testing. The arrangement of the strain gauges and extensometers are shown in Figure 2.

Plate 1: Strain Gauges installed in the test pile

The test piles, BTP-01 and BTP-02, had lengths of approximately 50m and 34m, respectively. The friction of the pile shaft would take up part of the applied load during testing. To maximize bearing capacity, a left-in casing with a 1mm thick bituminous coating on the outer surface was used as a sleeve. When estimating the applied load for the test, an allowance of 30kPa friction was considered for the shaft resistance along the pile shaft. The arrangements are shown in Figure 2.

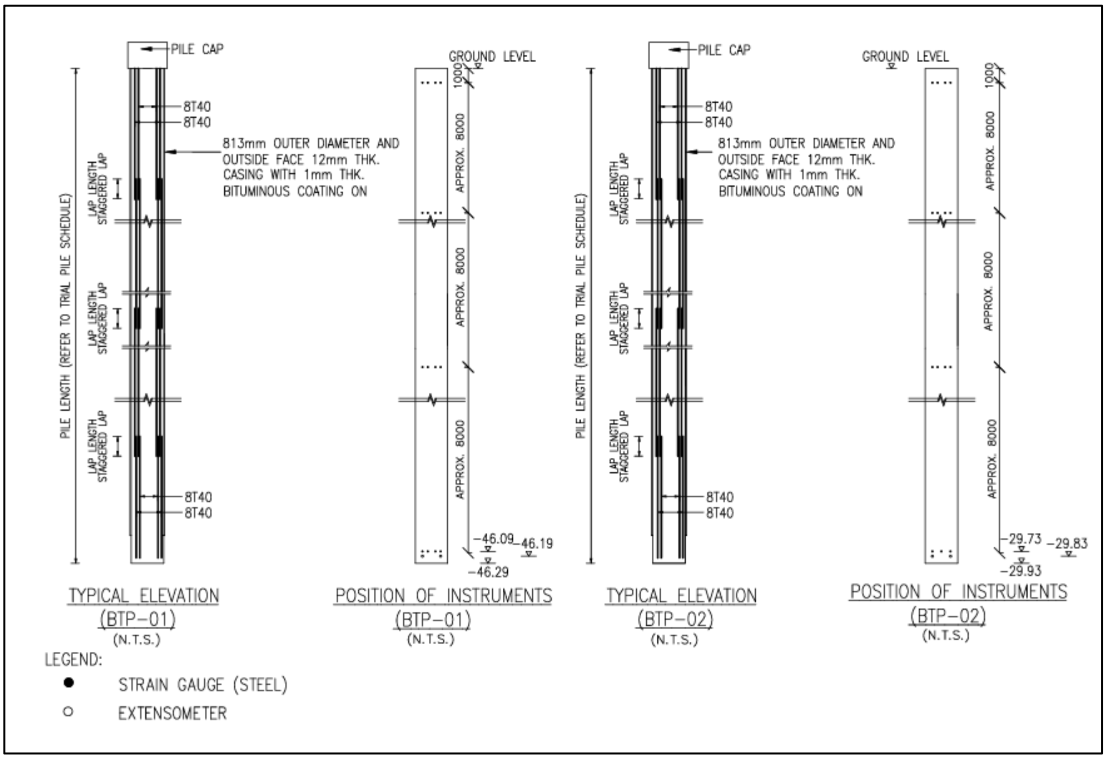

Figure 2: Arrangement of Strain gauges and extensometer for BTP-01 & BTP-02

Based on the pile length, the estimated maximum applied load to the two test piles are summarized in Table 4 below:

Table 4: Summary of estimated apply load for BTP-01 & BTP-02

Test Pile No.	Casing Length (m)	Friction allowance (kN)	End Bearing Force (kN)	Estimate Min. Test Load (kN)
BTP-01	50.31	3,831	7,787	11,618
BTP-02	33.85	2,571	7,787	10,358

The loading tests were conducted in 3 loading cycles. As the aim of the load test was to verify the allowable end bearing pressure of 5,000kPa with a factor of safety of 3, some allowance was also made to cater the shaft friction. The actual applied load at pile head for the two test piles are summarized in Table 5 below:

Table 5: Summary of actual apply load for BTP-01 & BTP-02

Cycle	Design Test Load	Actual Applied Load		Holding time
		BTP-01	BTP-02	
1	1W	4067	3626	-
2	2W	7940	7078	-
3	3W	11814	10531	72 hours

Plates 2 and 3 showing the kentledge setup and loading arrangement for the pile test.

Plate 2: Kentledge set up for load test

Plate 3: Loading arrangement

Pile Load test Results

The load along pile shafts for the two test piles were estimated based on the change of strains measured by strain gauges embedded in the pile shafts. Figures 3 and 4 show the pile loads versus the depths, it is clearly that some loads were taken up the pile shaft frictions and the pile loads at the pile bases were measured by the strain gauges located at 0.2m above the pile base. Based on the test results, the measured shaft friction estimated based on strain gauges were 24kPa and 22KPa for test piles BTP-01 and BTP-02 respectively which were less than the 30kPa assumed in the test proposal. So, the actual mobilized bearing pressure would be greater than 15,000kPa under the maximum test load.

The acceptance criterion of the load test is determined by the pile base settlement. The test is considered acceptable if the pile base settlement is less than 1.5% of pile base diameter under 3 time the working load (FoS of 3). The pile base settlement is measured by extensometers and can also be estimated by the strain gauges readings. The measured pile base settlement is 9.368mm and 9.385mm for BTP-01 and BTP-2 respectively under the maximum test load which is less than the allowable limit of 12.2mm (1.5% of the pile base diameter). The pile head and pile basement movement versus the applied load for BTP-01 and BTP-02 are show in Figure 5 and 6 respectively. The pile load at pile base is estimated by the measured change in strain and thus the mobilized end bearing pressure can be estimated. The estimated bearing pressure under the maximum test loads are 16,254kPa and 16,990kPa for BTP-01 and BTP-02, respectively. Assuming a FoS of 3, the estimated allowable bearing pressure were calculated as 5,418kPa and 5,663kPa, respectively.

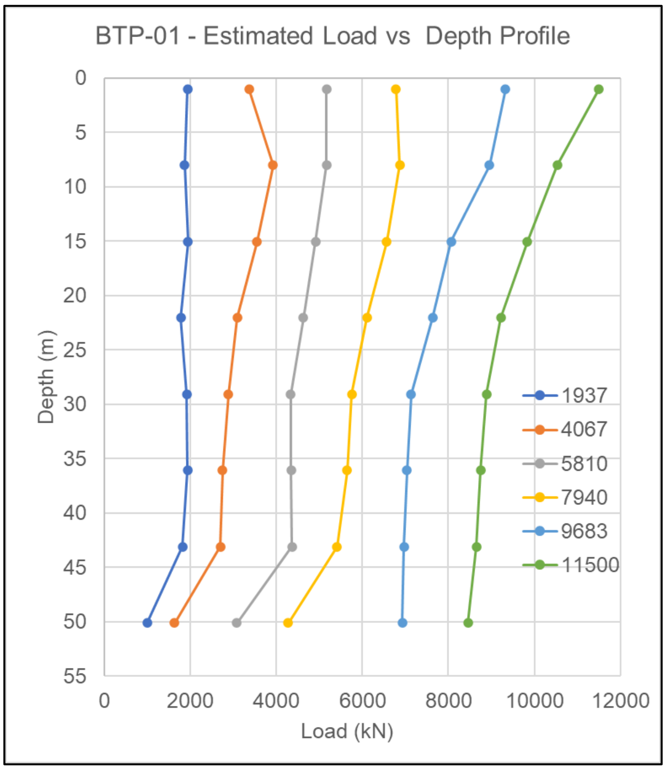

Figure 3: Load vs depth profile of BTP-01

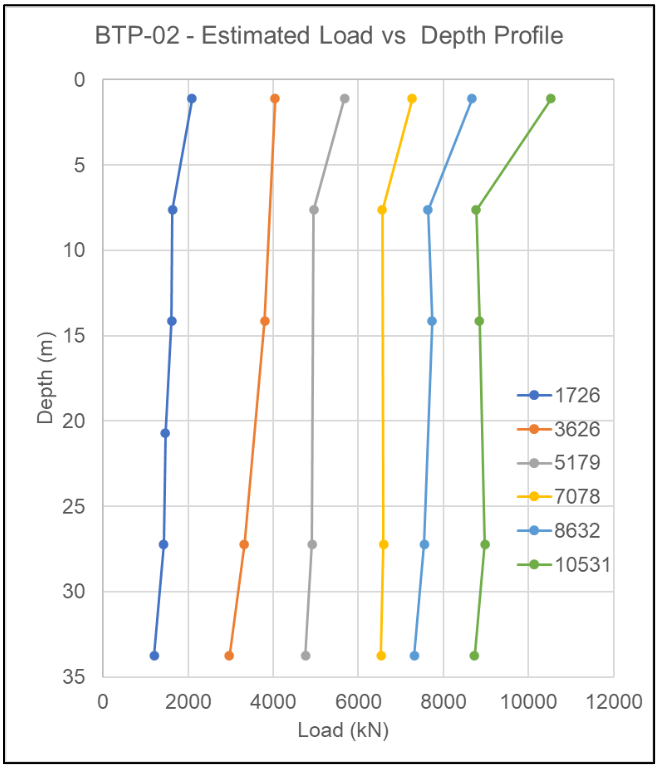

Figure 4: Load vs depth profile of BTP-02

By analysis of the plot of mobilized end bearing pressure against measured pile base movement during the pile loading test (Figures 5 & 6), it is evident that the pile behaved elastically, with no evidence of plasticity/strain softening even under the maximum test load. Previous results reported by Hill et al. (2000) also showed a mobilized bearing pressure of 26,500kPa for 14mm pile base movement in meta-siltstone, which is significantly higher than the currently adopted bearing pressure (>8,800kPa for a safety factor of 3).

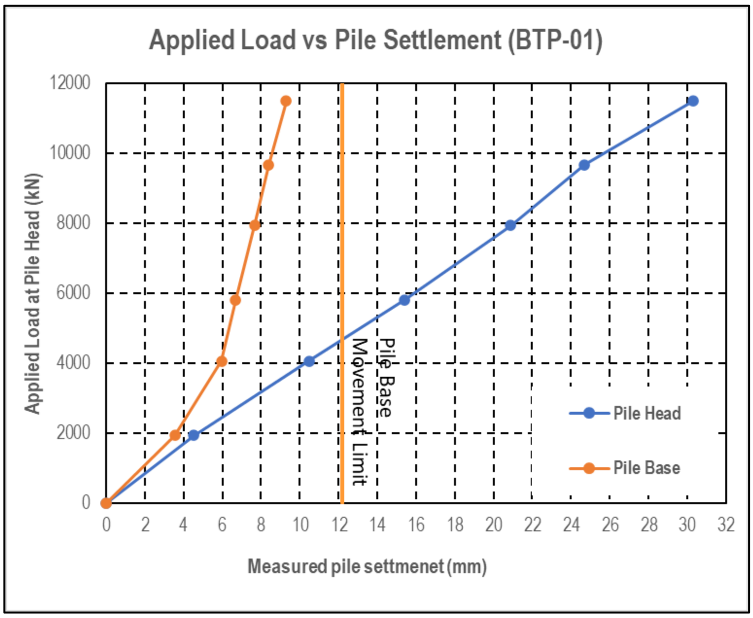

Figure 5: Load and Pile Movement Curve of BTP-01

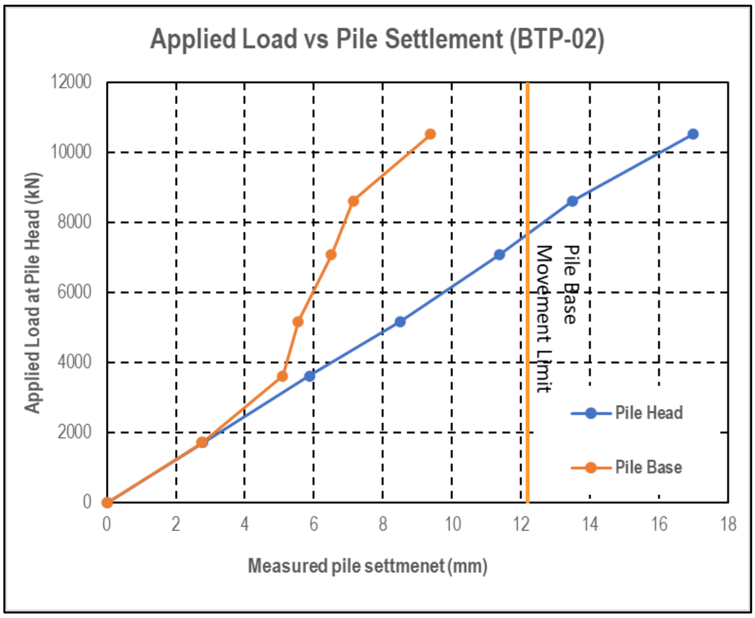

Figure 6: Load and Pile Movement Curve of BTP-02

DISCUSSION

Thorne (1980) proposed that expressing the bearing capacity of rock in relation to the UCS offers a valuable basis for evaluating the performance of foundation on rock. Irfan & Powell (1991) reported that an allowable bearing stress approximately 0.3 times the UCS would appear to be quite conservative for all rocks except swelling shales. Hill et al (2000), drawing from loading tests conducted during the West Rail Project, suggested a correlation between the ultimate bearing capacity and 1.0 times the UCS, with a maximum limit of 25MPa. It is worth noting that this upper limit represents the maximum bearing pressure demonstrated in the conducted tests. It is considered that the material strength of rock plays a crucial role in determining the ultimate bearing stress of foundation rock. However, in current design practices, it appears that the end bearing capacity of meta-sedimentary rock is not directly influenced by the material strength of the rock. This phenomenon can be attributed to the challenges associated with acquiring high-quality rock samples for strength testing, primarily due to the presence of closely spaced sub-horizontal joints commonly found in meta-sedimentary rock.

In the context of metasedimentary rocks encountered in the NM, it is frequently observed that these rocks exhibit layered structures with sub-horizontal joints. These rocks tend to preserve the original sedimentary layers present in their pre-metamorphic state, reflecting changes in sedimentary deposition or composition through distinct bands or layers within the rock. It is important to note, however, that not all meta-sedimentary rocks display such layering or sub-horizontal joints. For instance, marble, quartzite, and meta-conglomerate typically lack layered structures.

A comprehensive database of instrumented pile loading test results, encompassing the tests conducted at the West Rail Tin Shui Wai Station, has been compiled in GEO Publication 1/2006 (GEO, 2006). The summarized findings from both the aforementioned tests and those from the Tin Shui Wai Station are presented in Table 6. Notably, all four tests exhibited a maximum mobilized bearing pressure exceeding 15,000kPa, indicating the elastic behaviors of the piles under the maximum test loads.

Table 6: Summary of test results in meta-sedimentary rock

Pile No.	Pile diameter (mm)	Rock Strength (MPa)	Mobilized end bearing pressure (kPa)	Pile Base settlement (mm)
TSW1	1200	62 (UCS)	26,530	13.6
TSW2	1350	25.9 UCS)	24,000	2
BTP-01	813	1.8 (PLI_{50})	16,254	9.386
BTP-02	813	50.9 (UCS)	16,989	9.385

CONCLUSION

The instrumented loading tests conducted at the Kiu Cheong Road Site, along with the previous tests at the West Rail Tin Shui Wai Station, suggest that the allowable bearing stress of 3,000kPa for meta-sedimentary rock is very conservative. The two tests discussed in this paper together with the load tests carried out for the West Rail Project for the same rock type are generally consistent and the assumption of 5,000kPa would still be conservative. It is recommended to include the material strength of rock, similar to granitic and volcanic rock type, as a criterion in determining the presumed allowable bearing pressure of the meta-sedimentary rock. That is, an allowable end bearing stress of 5,000kPa for Grade III or better meta-sedimentary rock with TCR not less than 85% and USC not less than 25MPa/PLI_{50} not less than 1MPa shall be adopted for general foundation design.

PUBLISHER'S NOTE

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