Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1566

Performance Review of Foundations on Karstic Marble Formation

Sylvia Chik, Gloria Lee, Regis Chee, Eric Sze, Patrick Wong
Geotechnical Engineering Office, Civil Engineering and Development Department, Government of the Hong Kong Special Administrative Region, Hong Kong SAR, China, sylviachik@cedd.gov.hk

ABSTRACT: The presence of karstic marble formation has been posing significant challenges to the geotechnical engineering design in some development areas in Hong Kong. The marble, because of its carbonate content, is highly susceptible to dissolution by groundwater flow. The resulted cavities could be voids, underground channels, rockhead overhang and steep rock cliff thereby contributing significant risks to the foundation design. To facilitate rapid urban developments in the marble areas in late 1980s, a comprehensive engineering planning, design, construction supervision and long-term monitoring system had been put forward by the authority to ensure safe and economic developments. For example, the Geotechnical Engineering Office (GEO) developed a marble site classification system to categorise the hazard of karstic marble, and recommended design guidelines for foundations on karst. In order to assess the long-term performance of foundations in these difficult sites, and to evaluate the adequacy of the recommended design practice, the GEO has been imposing long-term building settlement monitoring requirement for high-rise building structures that are founded on karstic marble formation.

Since then, long-term monitoring for more than 30 sites, where buildings are supported by driven piles or end-bearing bored piles, has been carried out covering monitoring periods up to 20 years. Both building vertical settlements and differential settlements have been analysed with reference to the karstic marble ground condition of the sites as well as the type of foundations and building structures. This paper presents a holistic review of the planning strategy, design approaches and performance monitoring results of foundations on karstic marble over the past decades, together with findings on the adequacy of the prevailing engineering standards and practice on the foundation works in marble sites.

KEYWORDS: marble, marble karst, foundation, settlement.

1 INTRODUCTION

The first geological map of Hong Kong, published in 1936, highlighted the geology of Hong Kong is dominated by granitic and volcanic rocks. The presence of marble in the region remained unconfirmed until the first documented evidence emerged from ground investigation boreholes drilled at the low-rise housing development 'Fairview Park' in Yuen Long in 1977 (Langford et al. 1989) and later at other region in Yuen Long in 1980 (Ha et al. 1981). At that moment, although marble formations has been discovered, the associated solution features encountered were relatively limited, therefore the impact on foundation design was minimal (Chan, 1996).

Later during the development of new Light Rail Transport (LRT) depot in Yuen Long during 1986 and 1987, the widespread extent of karstic marble with cavities were discovered (Pascall, 1987). This development involved the construction of seven residential buildings atop a commercial podium, and the ground investigation results unveiled significant marble dissolution, where cavities as high as 20 meters were discovered, and sinkholes with diameters of up to 4 meters formed during pumping test for investigation for feasibility of caisson foundation on-site (Pascall, 1987; Chan, 1996). These discoveries raised public concerns regarding the stability of foundations in marble areas.

Soon after, marble was also discovered in Ma On Shan area in 1989, and the area was examined regionally in 1990 and discovered that the marble area is confined in a relatively small strip comparing to the Yuen Long Area (Chan, 1996; Sewell, 1996).

In response, the Geotechnical Control Office (GCO, later renamed Geotechnical Engineering Office (GEO) in 1991) conducted a series of studies in the Yuen Long area and Ma On Shan area to investigate the marble extent, properties, existing foundation stability, sinkhole risk, and formulated foundation design standard for the marble area. Special geotechnical controls were established for construction in marble areas (Chan, 1996).

To date, following over three decades of implementing the foundation design standard in marble, this paper seeks to comprehensively evaluate the standard's application and the long-term monitoring of high-rise buildings erected in karstic marble regions.

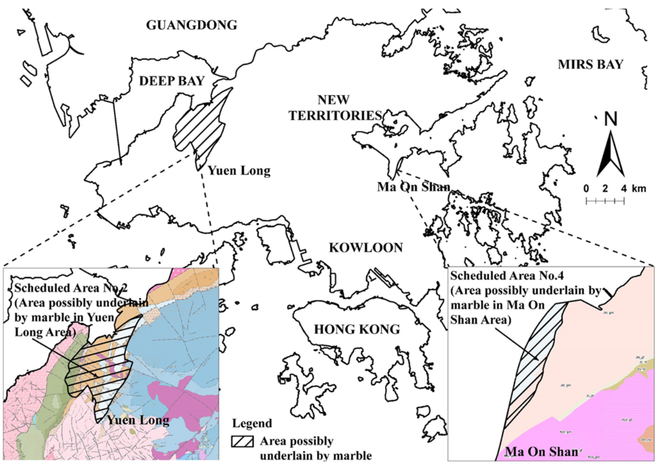

Figure 1. Areas of location with marble at Yuen Long area and Ma On Shan area (Simplified from Sewell (1996), So & Sewell (2019) and Tse & Tang (2024))

2 CHARACTERISTICS OF KARSTIC MARBLE FORMATION

2.1 *Yuen Long area*

Three marble-bearing Members have been identified within the Yuen Long area, with their spatial distribution illustrated in Figure 2 and their key properties detailed in Table 1 (GEO, 2007). To summarize, the Ma Tin Member of the Yuen Long Formation is predominantly composed of pure marble, interspersed with localized bands of dolomitic and siliceous dolomitic marble. The Long Ping Member of the Yuen Long Formation is characterized by grey to dark grey fine-grained marble, which is intercalated and interbedded with meta-sediments. The Tin Shui Wai Member of the Tuen Mun Formation comprises clasts of marble, quartzite, meta-siltstone, and other materials embedded within volcanic rocks. In terms of karst formation, the pure marble of the Ma Tin Member is highly susceptible to dissolution, whereas karst features are minimally developed in the Long Ping Member and the Tin Shui Wai Member.

The area possibly underlain by marble in Yuen Long area is named Scheduled Area No. 2.

Table 1. Properties of carbonate rocks in the Yuen Long area (GEO, 2007).

Member	Material Description	Karst Characteristics
Tin Shui Wai	*Marble Clasts within tuffaceous volcanoclastic rock*	*Dissolution of clasts is likely to be local and limited*
Long Ping	*Grey to dark grey marble. Locally impure. Interbedded with non-carbonate rocks*	*Irregular karst surface. Cavities generally less than 1m high.*
Ma Tin	*White marble. Generally pure*	*Highly irregular karst surface with pinnacles, depressions, overhangs and gullies. Cavities commonly 0.1 m to 2 m in length and less commonly up to 25 m high*

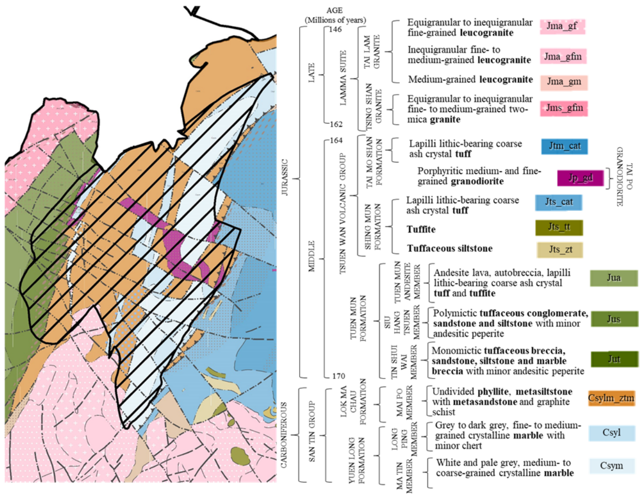

Figure 2. Simplified solid geology of Yuen Long area (Simplified from So & Sewell (2019) and Tse & Tang (2024))

2.2 *Ma On Shan area*

Only one marble-bearing formation, the Ma On Shan Formation, is located in the Ma On Shan area, with their spatial distribution illustrated in Figure 3 and their key properties detailed in Table 2 (Sewell, 1996; GEO, 2007). Like the Ma Tin Member in Yuen Long, this marble formation is relatively pure which is susceptible to dissolution, but it contains thin (less than 10 mm) interbeds of meta-siltstone. The Ma On Shan Formation is separated from the adjacent granite by a faulted contact, therefore the fault contact zone consists of highly sheared rock, including brecciated marble and siltstone. In certain areas, this rock has undergone mineralization and hydrothermal alteration to form skarn.

The area possibly underlain by marble in Ma On Shan area is named Scheduled Area No. 4.

Table 2. Properties of carbonate rocks in the Ma On Shan area (GEO, 2007).

Formation	Material Description	Karst Characteristics
Ma On Shan	*White to Grey Marble with thin (<10 mm) interbeds of meta-siltstone*	*Locally highly irregular karst surface. Cavities commonly 0.1 m to 2 m in length and less commonly up to 10 m high*

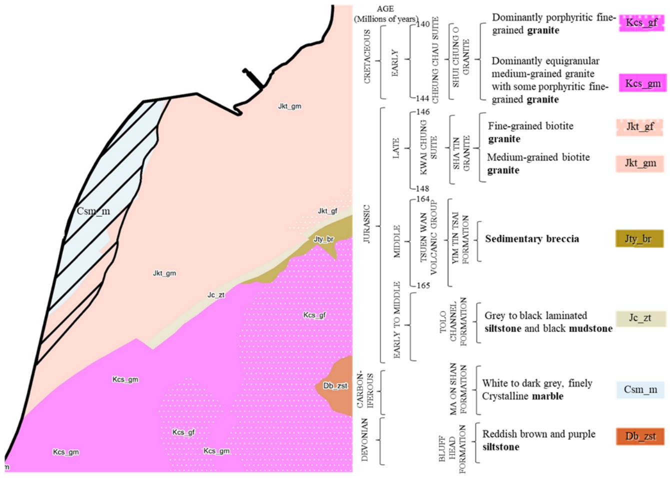

Figure 3. Simplified solid geology of Yuen Long area and Ma On Shan area (Simplified from Sewell (1996))

3 FOUNDATION DESIGN IN MARBLE

3.1 *Considerations and requirements*

Following the investigation of marble extent and properties, the GEO has formulated and recommended good practice and design guideline for foundation design in marble in aspects of ground investigation, design and construction and performance review (Chan, 1994; GEO, 2006; Buildings Department, 2024; GEO, 2025).

3.2 *Ground Investigation*

Regarding the ground investigation, to obtain an indication of the difficulty of designing and constructing foundations, a system of classifying of marble sites based on borehole data has been developed by Chan (1994). Chan (1994) developed a marble classification system, introducing the Marble Quality Designation (MQD) index, which categorizes the marble rock mass into five classes based on MQD values, core recovery, and Rock Quality Designation (RQD) (see Figure 4 and Table 3). Usually, marble class will be given to every 5 m sections of rock until the end of the borehole.

Table 3. Classification of Marble (Chan, 1994; GEO, 2006)

Marble Class	MQD Range (%)	Rock Mass Quality
I	*75 < MQD ≤ 100*	*Very Good; Rock with widely spaced fractures and unaffected by dissolution*
II	*50 < MQD ≤ 75*	*Good; Slightly fractured rock essentially unaffected by dissolution, or rock slightly affected by dissolution*
III	*25 < MQD ≤ 50*	*Fair; Fractured rock or rock moderately affected by dissolution*
IV	*10 < MQD ≤ 25*	*Poor; Very fractured rock or rock seriously affected by dissolution*
V	*MQD ≤ 10*	*Very Poor; Rock similar to Class IV marble except that cavities can be very large and continuous*

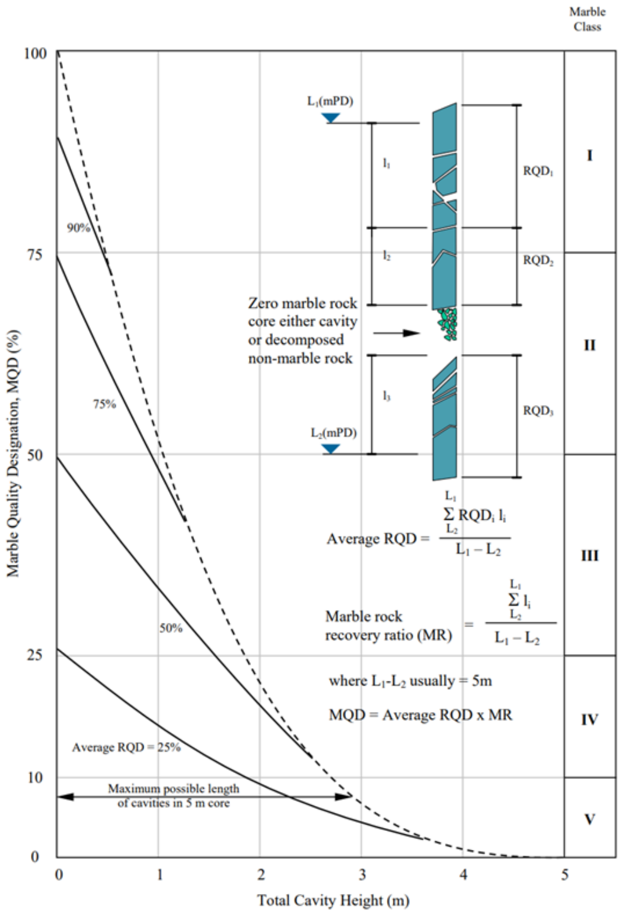

Figure 4. Definition of Marble Quality Designation (MQD) (Chan, 1994; GEO, 2006)

Additionally, rating can be given to each borehole according to the classes of marble revealed (Chan, 1994). A rating may be given to every karst morphology encountered in the borehole and the sum of rating is the borehole rating (Table 4). Then the sites are classified into four site class according to the percentage of problematic zones (Table 5). This system is instrumental in interpreting karst morphology and provides a framework for zoning sites based on foundation design and construction complexities.

Table 4. Borehole Rating (Chan, 1994)

Karst Morphology Encountered in the Borehole	Rating
Surface Karst – *a zone of Class III, IV, V marble mass at rockhead*	*0*
Overhang – *5-10 m of Class I, II marble mass capping the surface karst*	5
Class III marble separated by ≥ 5 m of class I, II marble mass from the surface karst	*10*
Class IV, V marble separated by ≥ 5 m of class I, II marble mass from the surface karst	*20*

Table 5. Marble Site Classification (Chan, 1994)

Percentage of area with borehole rating ≥ 5	Site Class	Description
0 – 10	*A*	*Easy Site*
10 – 25	*B*	*Fair Site*
25 – 50	*C*	*Very Difficult Site*
50 – 100	*D*	*Extremely Difficult Site*

It is also essential to collect sufficient ground investigation data to interpret the geology, i.e. to search for the extent and location of problematic area (e.g. karst, cavities) and the sound bearing strata. Therefore staged investigation to enable the planning of more intense boreholes at the problematic area, and drilling into 20m sound marble rock is recommended to investigate and ascertain the geological profile (Chan, 1994).

3.3 *Design and Construction*

Regarding the design and construction, the marble classification system by Chan (1994) is utilized to assess site conditions and guide engineering decisions. Key considerations include limiting the net increase in vertical stress at the marble surface to prevent overloading and collapse of the overhang slab at the top of the cavity (see Table 6) which shall be considered when designing shallow foundation or floating piles in soil strata (GEO, 2006).

Table 6. Limits on Increase of Vertical Effective Stress on Marble Surface (GEO, 2006)

Site Classification	Limits on Increase of Vertical Effective Stress on Marble Surface
A – Easy Site	*Design controlled by settlement in soil stratum*
B – Fair Site	*5 – 10 %*
C – Very Difficult Site	*3 – 5 %*
D – Extremely Difficult Site	*< 3 %*

For driven piles which are commonly designed to be driven to sound marble, as the piles driven to or through the karst features may be damaged during the hard driving, it is recommended to provide a strengthened pile base, and provide redundancy for piles (Chan, 1994; GEO, 2006). Chan (1994) recommended pile redundancy of 10 - 20 % for Easy Site and 20 – 30 % for Fair Site, where no simple rule exist for Very Difficult Site and Extremely Difficult Site.

End bearing piles founded on sound marble, such as large-diameter bored piles, is another common pile type adopted in karstic marble area. The key consideration is to make sure the founding sound marble has not been or has only slightly been affected by dissolution, such as Class I or II marble (GEO, 2025). It is critical to ensure that no major cavities are present within a stress dispersion zone below the pile base, defined by a specific angle (Chan, 1996).

4 FOUNDATION PREFORMANCE AND LONG-TERM SETTLEMENT MONITORING

4.1 *Performance review and long-term settlement monitoring*

Since the discovery of widespread extent of karstic marble with cavities in the 1980s, as there are very little experience in Hong Kong in foundation construction in karstic marble area at that time, performance review and long term settlement monitoring was introduced into the design practice to provide a 'norm' of performance against which the performance on particularly difficult sites can be evaluated.

To evaluate the sufficiency of the foundation design, performance review is recommended for high rise-building, usually at or higher than 20-storey, or other sensitive building over karstic marble area. Long term settlement monitoring during the superstructure construction and after the building is occupied in full usage is also recommended to review the foundation performance (ETWB, 2004; Buildings Department, 2021). This initiative aimed to collect sufficient settlement data to assess foundation performance in these geologically sensitive areas.

Settlement reading was taken at monthly interval after the completion of foundation construction to minimize scatter, and increasing to three-monthly later after several years of monitoring. The GEO will regularly review the settlement records and terminate long-term monitoring of those buildings that have shown to reach a steady state in settlement. Long term building settlement monitoring of the buildings may be ceased after sufficient data has been collected and reviewed.

4.2 *Review of monitoring results and foundation performance*

Throughout the years, long term settlement monitoring has been carried out for 34 development sites for 104 buildings. The most common type of foundation adopted in the karstic marble area are driven steel H-piles driven to refusal or driven to set which has reaching the karstic marble and large diameter bored piles founding into sound marble bedrock (i.e. Class I and II marble).

Figure 5 illustrates the settlement-time curves for three selected cases adopted driven steel H-piles, with detailed information on these cases provided in Table 7.

Table 7. Details of selected sites – Driven steel H-piles

Site	Type of Building	Type of Foundation
Site DH-A	*Two 35-storey towers on 1-level podium*	*Steel H-piles (305x305x223 kg/m and 356x368x174 kg/m) driven to refusal; Design allowable working pile load (for carrying dead + live load case) for 305x305x223 kg/m H-pile is 2900kN, and for 356x368x174 kg/m H-pile is 2300kN; Piles were driven close to the inferred marble bedrock surface; Piles were around 30 m to 45 m long; Site Class B; 25% pile redundancy was provided*
Site DH-B	*One 25-storey tower on 1-level podium*	*Steel H-piles (305x305x223 kg/m) driven to final set; Design allowable working pile load (for carrying dead + live load case) for 305x305x223 kg/m H-pile is 2900kN; Piles were generally driven on the marble karst surface, and some piles were driven through the marble karst surface; Piles were around 35 m to 45 m long; Site Class C; 25% pile redundancy was provided*

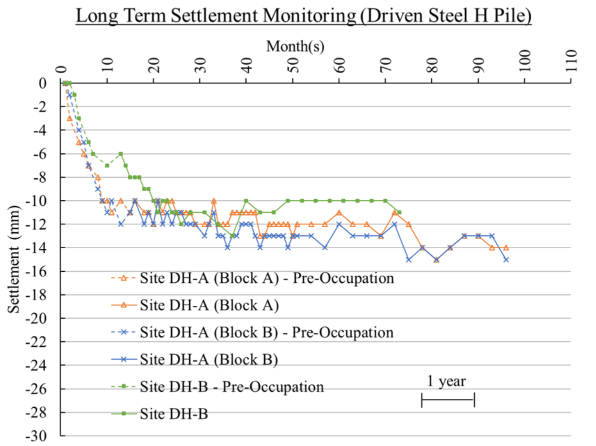

Figure 5. Settlement-time curve for three selected cases adopted driven steel H-piles

The data for the cases of driven steel H-piles indicates that an initial significant settlement occurs during the construction of the superstructure as well as during the occupancy phase, when the foundation is progressively loaded to its working capacity. The duration of this initial settlement varies. For instance, in Site DH-B, settlement continued to increase even after occupancy, whereas in Site DH-A, the initial settlement concluded before occupancy. In these cases, settlement stabilized to a more steady state between 13 to 21 months after the completion of the foundation structure.

Figure 6 shows the settlement-time curve for three selected cases adopted large diameter bored pile founded in sound marble, which is another common pile type in the marble area. The details of the selected cases are shown in Table 8.

Table 8. Details of selected sites – Large diameter bored pile founded in rock

Site	Type of Building	Type of Foundation
Site BP-A	*Five 25-storey towers with 4-level of podium*	*2m diameter bored pile; Piles passed through karstic zone and founded into sound marble (marble bedrock design bearing pressure: 10,000 kPa); Piles were around 20 m to 75 m long; No pile redundancy#*
Site BP-B	*Five 26-storey towers with 1-level of podium*	*2.2m/2.5m diameter bored pile; Piles passed through karstic zone and founded into sound marble (marble bedrock design bearing pressure: 7,500 kPa); Piles were around 53 m to 73 m long; No pile redundancy#*
Site BP-C	*Two 25-storey towers with 1-level of basement*	*2.5m diameter bored pile; Piles passed through karstic zone and founded into sound marble (marble bedrock design bearing pressure: 5,000 kPa); Piles were around 25 m to 55 m long; No pile redundancy#*

 # Pile redundancy only required for driven piles, and site classification is required to determine the redundancy recommended. Where the bored piles have pass through karstic zone and found on sound marble (i.e. Class I/II marble according to Figure 4), no pile redundancy is required (i.e. no site classification is required to be determined).

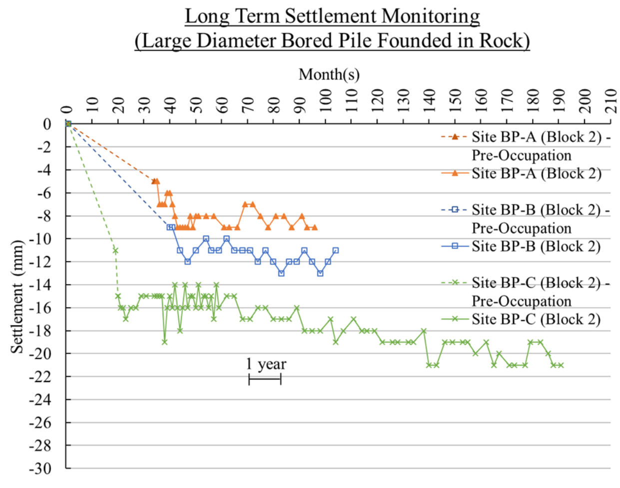

Figure 6. Settlement-time curve for three selected cases adopted large diameter bored piles

The bored piles in the three sites are generally found on Class I/II marble as defined according to the marble classification system by Chan (1994) (illustrated in Table 3), and the piles has been designed to avoid major cavities within a stressed zone below the pile bases according to the recommendation of GEO, 2025.

Same as driven-H piles, there were an initial significant settlement during gradual increase in superstructure load. In the bored pile cases, settlement has reached the more steady state after 23 to 44 months after completion of the foundation structure. All data shows small fluctuation in the monitoring during the steady period, which may due to some environmental factors such as thermal movement of the building material, deformation of piles under load variations (e.g. occupancy change). In Site BP-C (Block 2) shows a slight trend of settlement which is less than 1mm per year on average before around 150 months of monitoring and trending to an even smaller or minimal settlement trend afterwards. Block A and Block B in Site DH-A for driven steel-H pile also show a slight trend of settlement which is less than 1mm per year on average at the steady state too.

Buildings Department (2024) suggests the building settlement should generally not exceed 30mm and the tilting of the building should generally not exceed 1:500. The long term settlement monitoring of the above presented selected sites have been terminated, as the settlement and tilting monitored comply with that suggested in the code and the monitoring data shows minimal trend of settlement. Moreover, inspection of the general conditions of the buildings were conducted prior to recommending the termination of monitoring, with no abnormalities detected. Considering the building has been in-used for years and has experienced severe conditions like storms and typhoons, and corroborated by the fact that both settlement and tilting of the buildings remained within the limits specified in the code by Buildings Department (2024), the long-term settlement monitoring for these buildings was terminated.

Using the same reviewing method, the long term settlement monitoring for 30 out of 34 sites has been completed and terminated. The maximum total settlement of 27mm at individual building is recorded. The trending of settlement of those sites were less than 1mm per year on average within the last 3 years before termination of monitoring. Among all monitored sites, there are only 4 buildings having differential settlement greater than 1:1000, with a maximum value of 1:543. The recorded settlement and differential settlement fulfils the criteria set out in Buildings Department (2024). By building up the experience of successful case histories in constructing foundations in karstic marble area, this shows that the prevailing practice and standards on the design and construction of foundation in karstic marble formation mentioned above are sufficient to ensure the safety and satisfactory performance of the foundation works.

5 CONCLUSIONS

The presence of karstic marble formations in Hong Kong has long posed significant geotechnical challenges due to their susceptibility to dissolution, leading to cavities, irregular rockhead profiles, and potential instability. Over the past three decades, the GEO has developed a systematic approach to address these challenges, including the MQD system, borehole rating for marble bedrock and a site classification scheme (Chan, 1994; GEO, 2006; Buildings Department, 2024; GEO, 2025). These tools have proven essential in assessing karst hazards and guiding foundation design decisions, ensuring safe and stable construction in these difficult ground conditions.

Two primary foundation types, driven steel H-piles and large-diameter bored piles, have demonstrated long-term success in karstic marble areas. Driven piles, designed with redundancy (10–30% depending on site class) and strengthened bases, perform reliably when founded on or near sound marble. Large diameter bored piles founded into sound bedrock, which is usually Class I or II marble, with no major cavities presented within a stress dispersion zone below the pile base, also exhibit satisfactory performance. Additionally, for shallow foundation or floating piles in soil strata, limiting vertical stress increases on marble surfaces (3–10% depending on site classification) has effectively mitigated risk of overhang collapse.

The staged ground investigation process plays a crucial role in foundation design for karstic marble formations. By progressively refining the understanding of cavity locations and karstic zone extents through staged investigations, engineers can make informed decisions regarding foundation selection. In particularly challenging cases where severe karst features are identified, this process may even justify relocating planned high-rise structures to avoid zones classified as extremely difficult.

Long-term settlement monitoring data from over 30 development sites, spanning up to 20 years, confirms the effectiveness of these design practices. Total settlements remain within acceptable limits, with a maximum recorded value of 27 mm, which is below the 30 mm threshold specified in the Code of Practice for Foundations (2017). Differential settlements are generally minimal, with maximum tilting at 1:543. Initial settlements occur primarily during superstructure loading. During the post-stabilization period, long-term settlement rates are negligible (<1 mm/year), demonstrating the durability of these foundations even under extreme weather conditions such as typhoons.

This study by reviewing the long-term performance of the buildings in karstic marble area, provide a validated framework for foundation design in karstic environments. The integrated approach, including staged investigations, rigorous site classification, outlining design limits for different foundation types, and long-term monitoring, has provided a proven model for infrastructure development in karstic marble area, ensuring both safety and long-term performance.

6 ACKNOWLEDGEMENTS

This paper is published with the permission of the Head of the Geotechnical Engineering Office and the Director of Civil Engineering and Development, the Government of the Hong Kong Special Administrative Region of the People's Republic of China.

7 REFERENCES

Buildings Department 2021. *Geotechnical Control on Developments in Area Numbers 2 and 4 of the Scheduled Areas (Practice Note for Authorized Persons, Registered Structural Engineers and Registered Geotechnical Engineers No. APP-61).* Hong Kong SAR: Buildings Department, HKSAR Government, 7 p.

Buildings Department 2024. *Code of Practice for Foundations 2017 (2024 ed).* Hong Kong SAR: Buildings Department, HKSAR Government, 103 p.

Chan, Y.C. 1994. Classification and Zoning of Marble Sites (GEO Report No. 29). Hong Kong SAR: Geotechnical Engineering Office, Civil Engineering and Development Department, HKSAR Government, 38 p.

Chan, Y.C. 1996. Foundations in karst marble in Hong Kong. *Proceedings of the Twelfth Southeast Asian Conference on*

Geotechnical Engineering and Foundations, Kuala Lumpur, Volume II, pp 169-199.

Environmental, Transport and Works Bureau (ETWB) 2004. *Checking of Foundation Works in the Scheduled Areas of Northwest New Territories and Ma On Shan and the Designated Area of Northshore Lantau (Environment, Transport and Works Bureau Technical Circular No. 4/2004)*. Hong Kong SAR: Environment, Transport and Works Bureau, Hong Kong, 15 p.

GEO 2006. *Foundation Design and Construction (GEO Publication No. 1/2006)*. Hong Kong SAR: Geotechnical Engineering Office, Civil Engineering and Development Department, HKSAR Government,376 p.

GEO 2007. *Engineering Geological Practice in Hong Kong (GEO Publication No. 1/2007)*. Hong Kong SAR: Geotechnical Engineering Office, Civil Engineering and Development Department, HKSAR Government, 278 p.

GEO 2025. *Supplementary Guidelines for Foundation Design in Areas Underlain by Marble and Marble-bearing Rocks (GEO Technical Guidance Note No. 26)*. Issue 1 Revision B. Hong Kong SAR: Geotechnical Engineering Office, Civil Engineering and Development Department, HKSAR Government, 5 p.

Ha, T.H.C., Ng, S.K.C. and Li, Q.W. 1981. Discovery of Carbonate Rocks in the Yuen Long Area, Hong Kong. *Hong Kong Baptist College Academic Journal,* vol.8, pp 129-131.

Langford, R.L., Lai, K.W., Arthurton, R.S. and Shaw, R. 1989. *Geology of the Western New Territories. Hong Kong Geological Survey Memoir No.3*. Hong Kong SAR: Geotechnical Control Office, HKSAR Government, 140p.

Pascall, D. 1987. Cavemous Ground in Yuen Long, Hong Kong. Geotechnical Engineering. Vol. 18, pp 205-221.

Sewell, R.J. 1996. *Geology of Ma On Shan (Hong Kong Geological Survey Sheet Report No. 5)*. Hong Kong SAR: Geotechnical Engineering Office, Civil Engineering and Development Department, HKSAR Government, 45 p.

So, K.W.F. and Sewell, R.J. 2019. *Updating of Hong Kong Geological Survey 1:20,000-scale Maps Major Findings and Revisions Map Sheet 6 – Yuen Long (Geological Report No. GR 4/2019)*. Hong Kong SAR: Geotechnical Engineering Office, Civil Engineering and Development Department, HKSAR Government, 58 p.

Tse, T.K. and Tang, D.L.K. 2024. *Updating of Hong Kong Geological Survey 1:20,000-scale Maps Major Findings and Revisions Map Sheet 2 – San Tin (GEO Report No. 371)*. Hong Kong SAR: Geotechnical Engineering Office, Civil Engineering and Development Department, HKSAR Government, 40 p.