FOUNDATION DESIGN AND CONSTRUCTION ON KARSTIC ROCK FOR A 92-STOREY TOWER IN KUALALUMPUR, MALAYSIA

by

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ABSTRACT

The 92-storey Signature Tower in Kuala Lumpur is supported on a piled-raft foundation, where half of tower loads (≈ 3900 MN) are carried by (96) bored piles (D180 cm, L=18 m) socketed into karstic limestone and the other half is carried by the subgrade rock. Site investigation revealed infill cavities containing sand/silt mixture in some boreholes, posing challenges to design and construction of the foundation.

Static loading test by reaction system up to 76 MN (≈ 200% DL) and PDA test using an 8 MN (80 tonne) drop hammer were conducted to confirm the pile capacity. Instrumentation by strain gages, extensometers and "Distributed Strain Fiber Optic (DSFO)" were used to measure the mobilized strain and load transfers during loading test.

Lessons learn from design and constructions of piled-raft foundation are discussed including how to treat the cavities and to determine the pile lengths. Long-term monitoring using various instrumentation e.g., pressure cells to measure subgrade reaction, strain gages to measure load transfer of bored piles and strain-meters to measure deformation of raft foundation are being carried out to confirm the actual long-term performance of piled-raft foundation and compare to design prediction.

INTRODUCTION

The 92–storey Signature Tower in Kuala Lumpur is founded on karstic rock where infill cavities comprising of sand-silt mixture within limestone are found in some localized areas. Despite the fact that the limestone (RQD = 40-60%) is fairly strong, the presence of cavity prohibits the use of raft foundation alone due to potential of differential settlement. The use of "pure" piles foundation is expensive and time consuming. The compromise solution was to adopt a piled-raft foundation system, where tower loads are equally shared by bored piles and subgrade rock. The piles will bridge any cavity zones within the rock subgrade.

The study began with rock coring and laboratory testing to develop the subsurface profiles and design parameters for bored piles and subgrade reaction. A 3-D finite element software MIDAS was employed to perform piled-raft analyses by considering the construction sequence and rock-cavity layering. The pivotal inputs for piled-raft analyses are the pile capacity and load-movement relationship of the single pile and the subgrade reaction modulus of the underlying rock mass. This information is preferably obtained from full-scale pile loading test and large plate bearing tests.

During construction, probing tests were conducted at most tower pile locations to check for potential presence of a cavity; if found, injection grouting was performed to close the cavity. In addition, the pile length was adjusted (extended) by ignoring the shaft resistances from within the cavity layer.

Instrumented static loading tests were performed for compression and tension test piles up to 76 MN and -12 MN, respectively. The compression test for tower pile was conducted by reaction system, where strain gages, telltale and “Distributed Strain Fiber Optic (DSFO)” were used to measure the strain and load transfers. The tension test was conducted for podium pile where surface footings of 2 by 10 m were used to support the compressive reaction loads. The load-movement from these footing supports were used to generate the modulus subgrade reaction of underlying rock mass. This method is more reliable for developing the subgrade modulus as opposed to using small plate bearing tests where presence of cavities in the rock could exist and affect the response.

The results of the MIDAS analyses concluded that tower loads (3,900 MN) could be shared between bored piles and rock subgrade. Various instrumentations were installed in the rock, the bored piles, and mat reinforcement to monitor the performance of piled-raft foundation until the structure is completed (topping off).

SUBSURFACE CONDITIONS

The project site is located near the edge of the Kenny Hill formation where karstic features of limestone, such as steeply inclined bedrock, slime zone, sinkholes, cavities, pinnacles, and floaters (Fig.1) are often encountered posing challenges to design and construction of the pile foundation as experinced by the near-by PETRONAS Twin Towers.

The study began with intensive rock coring to establish representative subsurface stratigraphy and to identify the extent of cavity. During exploration, a geologist logged the core samples for examining the joint spacing, dip angles, Total Core Recovery (TCR), Rock Quality Designation (RQD), cavity thickness, and cavity material. Laboratory testing comprising unconfined compression test (UCT) to measure UCS (Uniaxial Compressive Strength), point load test (PLT), unit weight (γ), poisson ratio (ν), and elastic modulus of intact rock (E) were conducted to establish site-specific correlations between RQD vs. UCS and RQD vs. E. To determine the elastic modulus of representative rock mass (E_m), a correction factor (Fig. 2) was applied to modulus of intact rock (E).

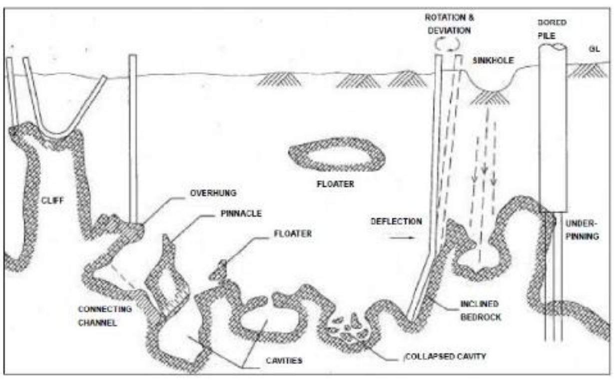


Fig. 1. Some Piling Problem in Limestone Formation (Neoh, 1998)

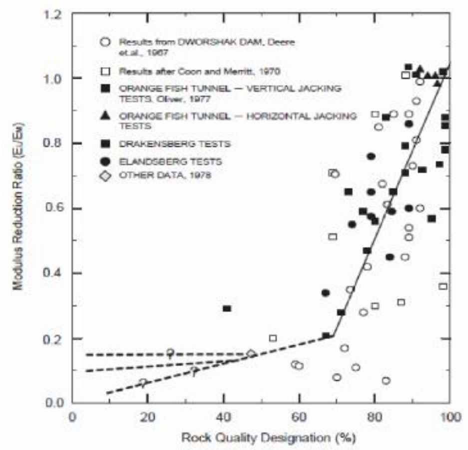


Fig. 2. Modulus Reduction Ratio to Intact Rock

Coring logs (Fig. 3) indicate that subsurface is underlain by fairly strong limestone (RQD = 40-60%) with infill cavity (sand-silt mixture) at sporadic depths and locations. After carefully review geologic features of the exposed rock and aware of unpredictable nature of cavity zone, it is assumed that 3-m cavity (modeled as medium dense sand) is present across the tower, beginning at 3 m below the raft foundation.

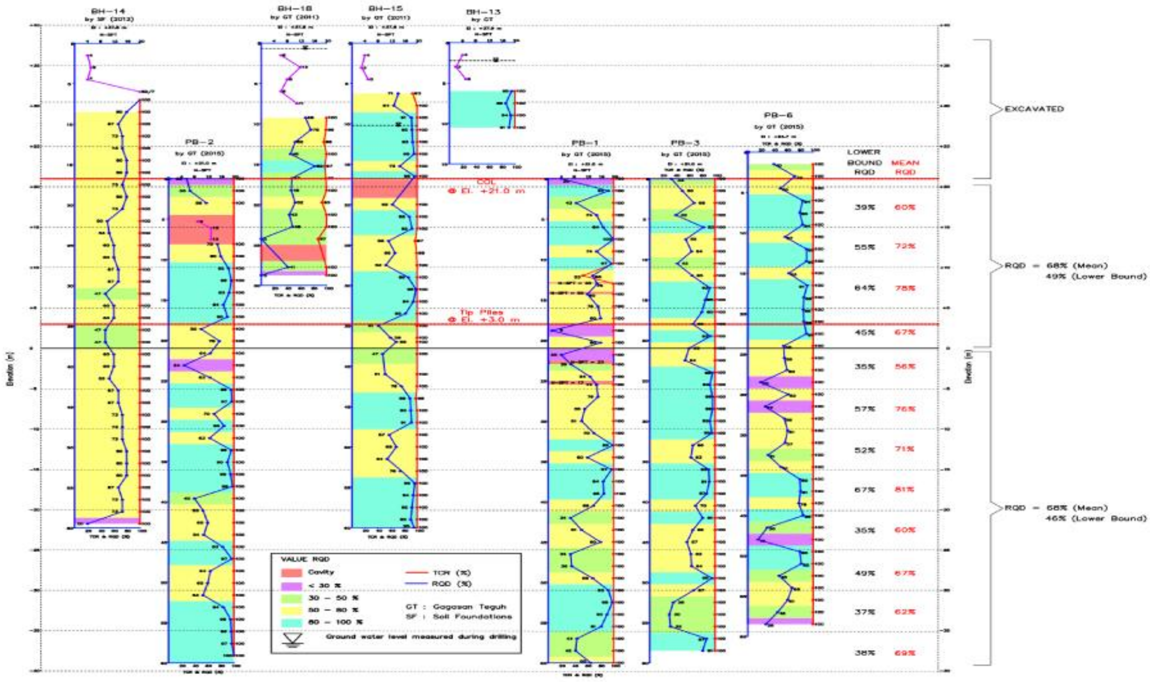


Fig. 3. Subsurface profile across tower site

PILED-RAFT ANALYSES

To perform “accurate” piled-raft analyses, two key input parameters are pivotal: a) pile capacity and load-transfer/load-movement relationships and b) modulus subgrade reaction and Young modulus of the underlying rock mass. It is common practice to perform full-scale loading tests to obtain these parameters and compare to design values. If they are different, refined analyses are warranted.

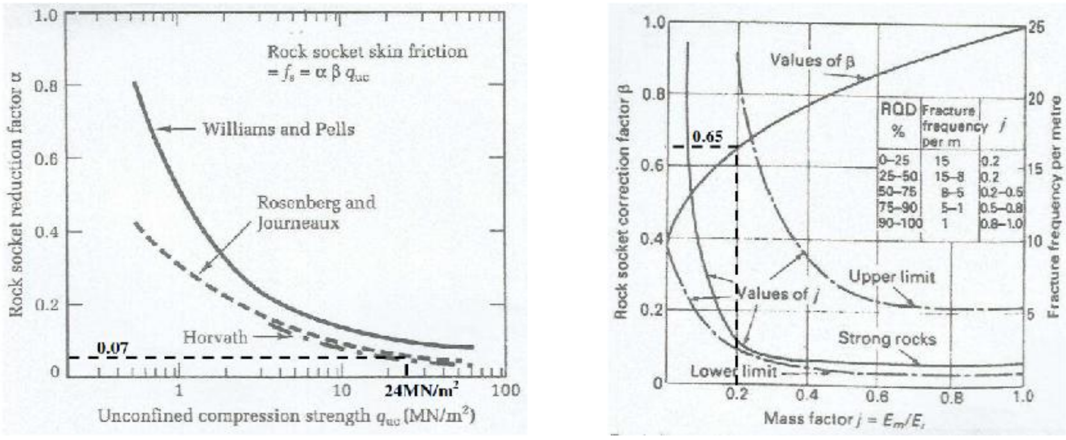
For bored piles socketed into the limestone, rock socket friction (f_s) is computed using empirical equations developed by Rosenberg & Journeaux (1976), Horvath (1978) and Williams & Pellis (1981) as based on the strength of intact rock (q_{uc}) and the quality of the rock mass due to discontinuities are shown below.

$$f_s = \alpha \times \beta \times q_{uc}$$

Where:

- q_{uc} is the unconfined (uniaxial) compressive strength of intact rock (UCS)
- α is a reduction factor as function of q_{uc} (Fig. 4a)
- β is a reduction factor as function of rock mass discontinuity (Fig. 4b)

Laboratory test indicates that for RQD = 40%, the design UCS is about 24 MPa, when using α = 0.07, β = 0.65 (Figs. 4a & 4b), a rock socket friction f_s of about 0.07 x 0.65 x 24,000 = 1,092 kPa. This is consistent with local practice, where (f_s) is 5% of unconfined compressive strength of rock or concrete, whichever is less. For limestone with UCS = 24 MP and concrete grade 60 with UCS = 60 MPa (cube strength), the computed f_s = 0.05 x 24,000 = 1,200 kPa.



(a) (b)

Fig. 4. (a) Reduction Factor (α) versus q_{uc}; (b) Reduction Factor (β) versus Rock Mass (after Tomlinson, 1995)

The safe (allowable) rock socket friction (f_s) is determined not only from theoretical estimate, but also from the results of instrumented loading tests of vicinity sites as well as intuitive judgment of minimum pile length with respect to tower heights. The project design adopts allowable rock socket friction of 400 kPa in compression and 200 kPa in tension by ignoring the pile base-bearing resistance. This is a prudent approach knowing effective cleaning of pile base for underwater construction is difficult to achieve. For transient (temporary) loading, such as wind load, the local code limits the load to 20% of the permanent (sustained) working load. For seismic loads are considered transient loads and are calculated for short and long period response values, S_{DS} and S_{D1} of 0.25 g and 0.08 g, respectively, and then multiplied by an "importance factor" of 1.5

The safe capacity of bored pile socket in fairly strong rock is mainly controlled by structural capacity of about 0.25% concrete grade (cube strength) used for the pile. According to local codes adopted from British codes, contribution of steel reinforcement in resisting the compression load is ignored. The allowable rock socket side shear determine the required length of bored piles, guard against overtuning of the tall tower due to wind loads (the prime transient load).

In this project, the tall tower is supported on (96) bored piles 1,800 mm diameter, effective length 18 m for 38-MN allowable working load. The subgrade rock is fairly strong with UCS = 24 MPa, E= 32,000 MPa and 3 m thick cavity beginning at 3 m below the raft foundation. The geotechnical 3D finite element software MIDAS-GTS-NX (version 2015) was used to compute the load distribution (pile and raft), displacement, induced stress and subgrade reaction on rock. The raft is modeled using solid element, the piles are modeled as pile elements and rock is modeled as a 3-D solid element following the Hoek-Brown constitutive model for jointed rock. Fig. 5 shows 3D modeling of the piled-raft foundation.

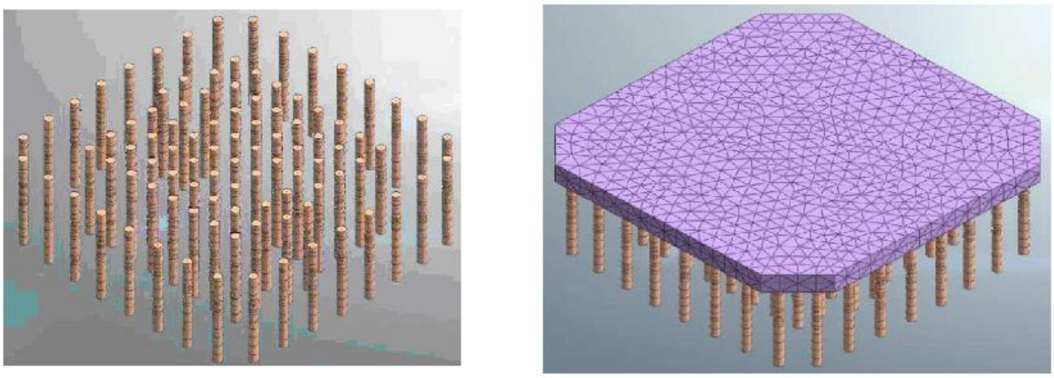
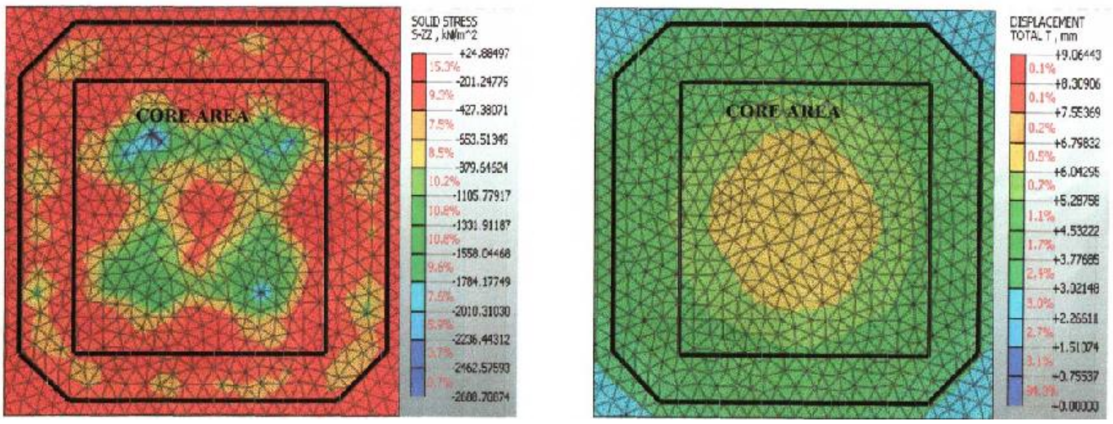


Fig. 5. 3D Modeling of Piled-Raft

The results of parametric MIDAS analyses show the computed displacement and induced stresses within subgrades (Fig. 6) where contribution of pile and raft are assured to have equal share in carrying the tower load. The average subgrade reaction is about 70,000 kN/m^3 (range 40,000-100,000 kN/m^3) and pile stiffness is about 5,250 kN/mm (range 4500-6000 kN/mm).



(Induced Stress) (Displacement)

Fig. 6. Displacement and Induced Stress from MIDAS

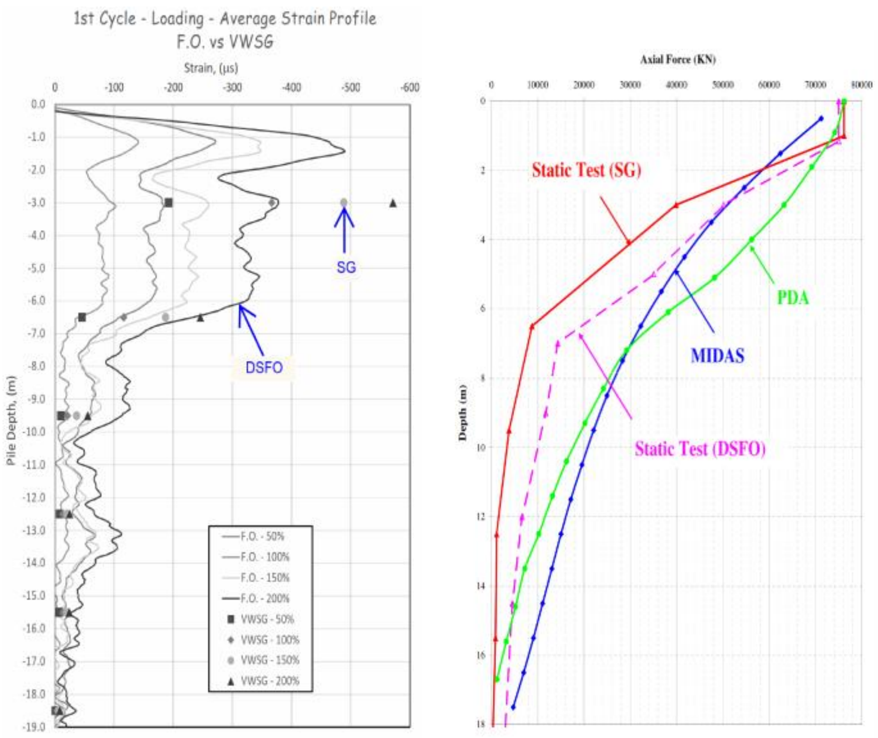
CONSTRUCTION OF PILED-RAFT FOUNDATION

The extent of cavity is relatively unknown, unpredictable, and risky to foundation safety, therefore, probing tests by rock coring to depths 5 m below the pile toe were conducted for most tower piles. If cavity and/or very fracture rocks (RQD< 10%) were found, injection grouting was performed for cavity treatment and pile length was adjusted (extended) by ignoring the shaft resistance in the cavity. Local practice in dealing with cavity was also implemented such as: a) If multilayer cavity with intermittent rock was found, the shaft friction contribution for intermittent rock less than 1 m thick was ignored, and b) if thick cavity (> 10 m) was encountered, the pile length was subject to effective pile embedment depth below 60 degree inclination from the lower bedrock level of the adjacent piles.

Among (96) tower piles, (23) piles encountered infill cavity with thickness varying from 2 to 12 m, such that pile lengths were extended from design 18 m to maximum 30 m. Additional shallow probing to 3-5 m deep was conducted near the cavity piles to assure no weak rock was present near surface subgrade (upper 3 m). As part of QA/QC during construction, each tower pile was subjected to Cross-hole Sonic Logging (CSL) and/or Low Strain Pile Integrity Test (PIT) test to confirm the structural integrity of each pile was good.

To verify the pile capacity and load-movement characteristic, a static compression-loading test by reaction system was conducted to 76 MN (200% DL = 38 MN). Strain gages, telltale and new device called “Distributed Strain Fiber Optic (DSFO)” were used to instrument the test pile. DSFO is a complimentary device to conventional strain gages, and allow measuring the pile strain continuously during loading test. At maximum peak load 76 MN, the movement at the pile head was about 8 mm and residual movement after unloading was 2 mm. Fig. 7a shows the strain profile measured from strain gages and the DSFO were fairly consistent, indicating the peak test load 76 MN was carried by shaft friction on the upper half length of the test pile and that no load had been transferred to the pile toe.

PDA tests using 8 MN drop hammer were performed on two test piles that representing normal and cavity piles. Load transfers from PDA test are consistent with static loading tests. Fig. 7b shows good comparison of load transfer curves from MIDAS, static and PDA tests, suggesting the input parameters for piled-raft analyses are reasonably representative.



(a) (b)

Fig. 7. (a) Strain profile (DSFO vs. strain gage); (b) Comparison of Load Transfers Curves

The tension-loading test on podium pile (D100 cm; L=11 m) was conducted up to -12 MN using support footings of 2 by 10 m in dimension. Under peak load -12 MN, each footing carried compression reaction load of 6 MN or equivalent to induced pressure of 300 kPa. The measured vertical movement was about 5 mm, resulting modulus subgrade reaction of about 60,000 kN/m^3, which is consistent with MIDAS model.

CONCLUSIONS

Design of super tall building on karstic rock requires engineering ingenuity, where unpredictable nature of cavity prohibits the use of raft foundation alone. The "pure" piled foundation alternative is costly and time consuming, especially if construction schedule is becoming a priority. Piled-raft foundation is an innovative compromise solution where bored piles will provide redundant supports to the building and to bridge any potential differential settlement due to the cavity soils.

This paper discusses the procedures how to develop sound design parameters of piled-raft foundation and to adopts local practice in dealing with cavity, from rock probing, injection grouting to adjustment of pile length. Full-scale loading tests are performed to confirm the design parameters of bored piles and subgrade modulus. A comprehensive QA/QC testings by CSL and PIT are performed to assure the structural integrity of each pile is sound.

To monitor the actual performance of piled-raft foundation, various instrument is installed after piling work is completed, which includes pressure cells to measure subgrade reaction of the rock, strain gages to measure axial load transferred to bored pile, and strain-meter to measure deformation and induced stresses of raft foundation. Intensive survey will also be performed to measure the building settlement. This monitoring will assure the safety of piled-raft foundation and the results can be compared to predicted MIDAS model. This work is still in progress until topping off, expected to be in 2018.

ACKNOWLEDGEMENT

The author expresses his sincere appreciation to the following individuals: a) Dr. Nicholas Sitar, a geological professor from UC Berkeley for his participation in this project, b) Dr. Bengt Fellenius who peer-reviewed the manuscript; c) Mr. Roland Suckling, the project's director for his permission to publish part of this study report, d) EDP engineers in Kuala Lumpur for sharing their local experiences in dealing with cavity rock, and e) Mr. Tee Bum Pin for sharing the strain gage and DSFO data.

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