RATIONALISATION OF CONVENTIONAL GEOTECHNICAL PRACTICE TO EC7 ON THE DESIGN OF PILE FOUNDATIONS UNDER AXIAL COMPRESSION LOAD

Yean-Chin TAN[1], See-Sew GUE[2] and Chee-Meng CHOW[3]
[1] *Director, G&P Geotechnics Sdn Bhd, Kuala Lumpur, Malaysia*
[2] *Managing Director, G&P Geotechnics Sdn Bhd, Kuala Lumpur, Malaysia*
[3] *Associate Director, G&P Geotechnics Sdn Bhd, Kuala Lumpur, Malaysia*
E-mail: gnp-geo@gnpgroup.com.my

ABSTRACT: Conventional geotechnical practice for the design of pile foundations is based on working state principles where a geotechnical engineer would determine the allowable pile capacity to support the 'unfactored' loads provided by a structural engineer. Although such approach has generally proved to be acceptable, it has nevertheless presented difficulties in terms of communication between structural engineer and geotechnical engineer. The need for harmonization between structural and geotechnical design practice is important especially for analysis involving soil-structure interaction. EN1997 Eurocode 7: Geotechnical Design (EC7) has presented a framework for geotechnical design based on limit state principles and many Asian countries which rely on European design codes (e.g. British, German, French, etc.) will be affected after withdrawal of the respective countries' design codes. As such, it is important for the affected countries to formulate appropriate National Annex for application in their own countries based on their own local experience. In this paper, suggestions on partial, correlation and model factors used in conjunction with Design Approach 1 of "alternative procedure" as per Clause 7.6.2.3 (8) of EC7 for pile design under axial compression loads based on Malaysian experience is presented to ensure smooth transition from current practice based on working state principles to the limit state design of EC7. The methodology presented in this paper can be adopted by other countries in formulation of their respective National Annexes based on their own local experience on pile performance.

1. INTRODUCTION

Geotechnical design of pile foundations in Malaysia is traditionally based on working state principles with estimation of pile allowable capacity based on semi-empirical method. The factors of safety (FOS) normally used in static calculation of allowable pile geotechnical capacity are partial FOS on shaft (F_s) and base (F_b) respectively, and global FOS (F_g) on total capacity. The lower geotechnical capacity obtained from both methods using the following equations is adopted as the allowable pile geotechnical capacity:

$$Q_{ag} = \frac{Q_{su}}{F_s} + \frac{Q_{bu}}{F_b} \qquad (1)$$

$$Q_{ag} = \frac{Q_{su} + Q_{bu}}{F_g} \qquad (2)$$

Note: Use the lower of Q_{ag} obtained from eq. 1 and eq. 2 above.

Where:

Q_{ag} = Allowable geotechnical capacity
Q_{su} = Ultimate shaft capacity = $\sum_i (f_{su} \times A_s)$
i = Number of soil layers
Q_{bu} = Ultimate base capacity = $f_{bu} \times A_b$
f_{su} = Unit shaft resistance for each layer of embedded soil
f_{bu} = Unit base resistance for the bearing layer of soil
A_s = Pile shaft area
A_b = Pile base area
F_s = Partial Factor of Safety for Shaft Resistance (generally 1.5)
F_b = Partial Factor of Safety for Base Resistance (generally 3.0)
F_g = Global Factor of Safety for Total Resistance (Base + Shaft) generally 2.0

The evaluation of shaft resistance and base resistance is commonly based on semi-empirical method based on correlations to N-values from Standard Penetration Tests (SPT 'N' values):

$f_{su} = K_{su} \times$ SPT'N' (in kPa)
$f_{bu} = K_{bu} \times$ SPT'N' (in kPa)

Tan & Chow, 2003, Tan et al., 2009 and Chow & Tan, 2009 discuss some of the commonly adopted design approaches in Malaysia.

The application of EC7 for pile design in Malaysia and other countries which rely on European design codes needs rationalization and harmonization with current established local practices that have been serving the construction industry well as there was no reported catastrophic failure of structures due to the failure of pile foundations under compression. In this paper, a general approach towards rationalisation of conventional Malaysian practice to EC7 on the design of pile foundations under axial compression load is presented. Suggestions on partial, correlation and model factors used in conjunction with Design Approach 1 of "alternative procedure" as per Clause 7.6.2.3 (8) of EC7 based on the presented approach are also presented. The general concepts presented in this paper should be equally applicable for other countries facing similar transition to EC7.

2. CONCEPT FOR APPLICATION OF EC7 TO LOCAL PRACTICE

2.1 General Approach

The application of EC7 to local practice should take into consideration the following aspects:

a) Comparison with local practice on adopted factors of safety. The National Annex for the particular country based on principles of EC7 should be calibrated with local practice to ensure smooth transition to EC7.
b) Review of current local practice on pile testing requirements. Comparison should be made to pile testing requirements of EC7 to ensure consistency.
c) Clear distinction between partial factors on resistance for shaft and base which are mobilized at different magnitudes of displacement respectively.

d) Calibration of partial factors with actual case histories/load test results.

2.2 Suggested Approach for Malaysian Practice

To ensure smooth transition to EC7, the followings are the main criteria which require rationalization and harmonization for application of EC7 in Malaysia for geotechnical design of pile foundations under compression load (Tan et al., 2009):

a) The partial factors should be in line with current partial factor of safety (FOS) on shaft (F_s), base (F_b) and global FOS (F_g) on total capacity that are extensively accepted and used in Malaysia.
b) There should be a clear distinction between the partial factor of safety for shaft and base which are mobilized at different magnitude of displacement.
c) Requirements for pile testing especially static and dynamic load tests on preliminary piles (sacrificial piles) to be loaded to failure and also working piles to be loaded to a designed test load.
d) The adoption of the same Model Factor as in United Kingdom's National Annex (UK-NA).
e) The adoption of EC7 concept of allowing lower partial factor if more verification tests (e.g. static or dynamic load tests) are carried out at a site.
f) The suggested partial factors need to be verified with actual case histories to review the reliability of the suggested values. More case histories are needed before the values of partial factors for Malaysian National Annex is finalized.
g) Complying to methodology outlines in EN1997-1, 7.6.2.3(8) where the characteristic values may be obtained by:

$$R_{b;k} = A_b\, q_{b;k} \quad \text{and} \quad R_{s;k} = \sum_i A_{s;i} \cdot q_{s;i;k} \qquad (3)$$

where
$q_{b;k}$ and $q_{s;I;k}$ are characteristic values (in kPa) of base resistance and shaft friction in the various strata, obtained from values of soil/rock parameters.
$R_{b;k}$ and $R_{s;k}$ are characteristic base and cumulative shaft resistance (in kN).

Note: In order to apply this procedure, the values of the partial factors for resistance such as base (γ_b), shaft (γ_s) and combined (γ_t) may need to be corrected by a model factor in which UK-NA recommends a value of 1.4, except that it may be reduced to 1.2 if the resistance is verified by a maintained load test taken to the calculated, unfactored ultimate resistance.

EC7 also covers other methodologies as follows:

7.6.2.2: Ultimate compressive resistance from static load tests.
7.6.2.3: Ultimate compressive resistance from ground test results (except 7.6.2.3(8)).
7.6.2.4: Ultimate compressive resistance from dynamic impact tests.
7.6.2.5: Ultimate compressive resistance by applying pile driving formulae.

However, these methodologies will not be discussed in this paper and will be addressed separately in the future.

Based on the above concepts, different sets of partial factors are suggested for driven pile, bored pile and jack-in pile. Even though jack-in pile can be categorised as displacement pile which is the same as driven pile, there is notable differences in the behaviour of jack-in pile compared to traditional driven pile which warrants a separate sets of partial factors. Chow & Tan, 2009 and Chow & Tan, 2010 discuss some of the observed behaviour of jack-in pile and its effect to pile design.

3. SUGGESTED PARTIAL FACTORS FOR MALAYSIAN NATIONAL ANNEX OF EC7 FOR PILE FOUNDATIONS UNDER COMPRESSION LOAD

Based on the general concept outlined, Table 1 summarises the partial factors for actions, soil materials and resistance suggested for Malaysian National Annex (MY-NA) to EC7 for driven piles, bored piles and jack-in piles.

From Table 1, it can be seen that the partial factors for driven piles and jack-in piles are essentially the same. The main difference between driven piles and jack-in piles is in the suggested model factor. For jack-in pile, the model factor suggested is generally lower with value of 1.3 (compared to 1.4 for driven piles) and 1.1 (1.2 for driven piles) if the resistance is verified by static load tests taken to the calculated, unfactored ultimate resistance. The main rationale behind the lower model factor is based on EC7's principles which allow lower partial factors if testing on preliminary piles to ultimate resistance is carried out on site to verify the load capacity. This is evident from the reduction of model factor from 1.4 to 1.2 if there is a preliminary pile static load test which is loaded to unfactored ultimate resistance (e.g. failure load).

As such, the lower model factor suggested for MY-NA is based on the following considerations for jack-in piles:

a) Every jack-in pile during installation is jacked (loaded) to two (2) times the design load or more, and held for 30 seconds to record settlement for at least two (2) cycles and this is similar to carrying out a "static" load test in a very short holding time. Despite it being not exactly the same as a static load test, the quality control and verification of load capacities for jack-in piles is more rigorous and more assured compared to other pile types (e.g. driven piles, bored piles and micropile) which are not "test loaded" during installation. Therefore, the suggested model factor value should be smaller than that of driven piles and bored piles in line with the concept of EC7 allowing lower model factors with more testing.

b) For consistency in design, it is suggested that the partial factors for resistance (shaft, base and combined) in jack-in piles should follow those of driven piles when adopting design approach outlined in EN1997-1, 7.6.2.3(8). This is because both driven and jack-in piles are generally displacement type of pile foundations and base capacity will not be reduced due to disturbance as in bored piles. However, the ultimate shaft resistance and base capacity for jack-in piles are often higher compared to driven piles (Chow & Tan, 2010).

Based on the suggested partial factors in Table 1, comparisons are made to conventional factors of safety (FOS) adopted in current Malaysian practice. The comparison is made by combining the various partial factors of safety suggested for MY-NA to an "equivalent" FOS. The ratio of permanent load (e.g. dead load) to variable load (e.g. life load, etc.) is taken as 8:2 when calculating the "equivalent" FOS. Table 2 summarises the "equivalent" factors of safety based on suggested Malaysian National Annex for EN1997-1:2004 for driven piles and jack-in piles.

From Table 2, it can be observed that the suggested partial factors for MY-NA will produce "equivalent" FOS which ranges from 1.52 to 2.37 for total/combined capacity compared to current Malaysian practice of 2.0. The "equivalent" FOS for shaft capacity ranges from 1.17 to 2.23 while the "equivalent" FOS for base capacity ranges from 1.67 to 2.82. The suggested partial factors of safety is also found to be conservative based on actual load test results compiled by Tan et al., 2009 and Chow & Tan, 2009.

Table 1 Summary of Partial Factors for Actions, Soil Materials and Resistance Suggested for Malaysian National Annex (MY-NA) EN1997-1:2004.

			Design Approach 1								
			Combination 1			**Combination 2 – Piles**					
						WITHOUT explicit verification of Serviceability Limit State (SLS)[A]			**WITH explicit verification of Serviceability Limit State (SLS)**[A]		
			A1	**M1**	**R1**	**A2**	**M1**	**R4**	**A1**	**M1**	**R4**
Actions	**Permanent**	**Unfavorable**	**1.35**	▨	▨	**1.00**	▨	▨	**1.00**	▨	▨
		Favorable	**1.00**	▨	▨	**1.00**	▨	▨	**1.00**	▨	▨
	Variable	**Unfavorable**	**1.50**	▨	▨	**1.30**	▨	▨	**1.30**	▨	▨
Soil	**tan ϕ'**	▨	▨	**1.00**	▨	▨	**1.00**	▨	▨	**1.00**	▨
	Effective cohesion	▨	▨	**1.00**	▨	▨	**1.00**	▨	▨	**1.00**	▨
	Undrained strength	▨	▨	**1.00**	▨	▨	**1.00**	▨	▨	**1.00**	▨
	Unconfined strength	▨	▨	**1.00**	▨	▨	**1.00**	▨	▨	**1.00**	▨
	Weight density	▨	▨	**1.00**	▨	▨	**1.00**	▨	▨	**1.00**	▨
Driven piles or Jack-in piles[B]	**Base**				**1.1**			**1.9**			**1.8**
	Shaft (compression)				**1.0**			**1.5**			**1.0**
	Total / combined				**1.05**			**1.6**			**1.3**
Bored piles	**Base**				**1.2***			**2.2***			**1.8***
	Shaft (compression)				**1.0**			**1.5**			**1.1**
	Total / combined				**1.1**			**1.6**			**1.4 (1.3)****

[A] The lower partial factor of safety in R4 may be adopted

a) if serviceability is verified by static load tests (preliminary and/or working) carried out on in accordance with the pile testing criteria listed in ***Table 3****(MY-NA suggestion)*, OR

b) if settlement is explicitly predicted by a means no less reliable than in (a), OR

c) if settlement at the serviceability limit state is of no concern

A ***model factor*** should be applied to the shaft and base resistance calculated using characteristic values of soil properties by a method complying with EN1997-1, **2.4.1**(6). The value of the ***model factor*** should be **1.4**, except that it may be reduced to **1.2** if the resistance is verified by a static load test taken to the calculated, unfactored ultimate resistance. (To follow NA to BS EN 1997-1:2004)

* For bored pile design, the base resistance should be ignored (not included in calculation) unless for bored pile constructed in dry hole, or with base grouting, or with fully instrumented preliminary pile loaded to failure and ultimate base capacity verified on site.

** Partial factors for Total/Combined capacity of bored pile can be reduced to 1.3 if base is ignored in the calculation of the total/combined capacity.

[B] For ***Jack-in Piles***, ***model factor*** should be applied to shaft and base resistance calculated using characteristic values of soil properties by a method complying with EN1997-1, **2.4.1**(6). The value of the ***model factor*** should be ***1.3***, except that it may be reduced to ***1.1*** if the resistance is verified by static load tests taken to the calculated, unfactored ultimate resistance.

In order to qualify using a lower model factor of 1.2 and 1.1 for driven and jack-in piles respectively, a preliminary (sacrificial) pile should be subjected to a static load test (SLT) taken to the calculated, unfactored ultimate resistance as follows:

a) Load to at least 2.5 times the design load or to the failure of the pile to try to obtain ultimate resistance of pile for shaft and base and to determine settlement characteristic of the pile.

b) Instrumentation is encouraged to allow proper verification of load-settlement behaviour in shaft and also base.

c) Without SLT on preliminary pile to verify ultimate resistance, a Model Factor of 1.4 and 1.3 for driven and jack-in piles should be used instead.

Irrespective of design approach, proper and sufficient pile load verification tests should be carried out such as static load tests, dynamic load tests and sonic logging (for bored piles) to verify the acceptance of the pile.

Table 2 Summary of "Equivalent" Factors of Safety (FOS) based on Suggested Malaysian National Annex (MY-NA) for EN1997-1:2004

		DA1-C1 MY-NA	DA1-C2 MY-NA **WITHOUT explicit verification of SLS**	DA1-C2 MY-NA **WITH explicit verification of SLS**
Model Factor =1.4				
Driven Pile	**Base**	**2.13**	**2.82**	**2.67**
	Shaft	**1.93**	**2.23**	**1.48**
	Total	**2.03**	**2.37**	**1.93**
Model Factor =1.3				
Jack-in Pile	**Base**	**1.97**	**2.62**	**2.48**
	Shaft	**1.79**	**2.07**	**1.38**
	Total	**1.88**	**2.20**	**1.79**
Model Factor =1.2				
Driven Pile	**Base**	**1.82**	**2.41**	**2.29**
	Shaft	**1.66**	**1.91**	**1.27**
	Total	**1.74**	**2.03**	**1.65**
Model Factor =1.1				
Jack-in Pile	**Base**	**1.67**	**2.21**	**2.10**
	Shaft	**1.52**	**1.75**	**1.17**
	Total	**1.59**	**1.86**	**1.52**

To fulfil the requirement "**<u>WITH</u>** explicit verification of SLS" for MY-NA, the testing criteria for piles under compression load should satisfy items (1) and (2) stated below:

1) Static Load Test (SLT) on Working Pile:

a. Load to 1.5 times design load. Acceptable settlement at pile cut-off level should be less than 10% of the pile diameter.(I)

b. Acceptable settlement at pile cut-off level should not exceed 12.5mm(II) at 1.0 times the representative load.

c. Acceptable residual settlement at pile cut-off level should not exceed 6.5mm(II) after full unloading from 1.0 times the representative load.

d. To fulfil criteria "With explicit verification of SLS" (as described in Table 1), the percentage (%) of constructed piles listed in Table 3 should be subjected to SLT (minimum one (1) pile).

Note:

(I) EC7, 7.6.1.1 (3) states "For piles in compression it is often difficult to define an ultimate limit state from a load settlement plot showing a continuous curvature. In these cases, settlement of the pile top equal to 10% of the pile base diameter can be adopted as the "failure" criterion". However, for very long piles, elastic shortening will need to be taken into account as the elastic shortening of the long pile itself may reach 10% of the pile diameter and in this scenario, the ultimate load should be defined by the Engineer taking into consideration the intended usage of the structure.

(II) The values indicated serve as a preliminary guide. Geotechnical Engineer and Structural Engineer should specify the project-specific allowable settlement at 1.0*Working Load (WL) and residual settlement to suit the buildings and structures to be supported by the pile.

2) (A) High Strain Dynamic Load Test (DLT) on Pile:

a. To fulfil the criterion "With explicit verification of SLS", a minimum percentage (%) of constructed piles listed in Table 3 should be subjected to DLT.(III)

Note:

(III) DLT can be omitted if it is technically not suitable to carry out DLT on the pile (e.g. bored pile with capacity solely relying on rock socket, etc.). Then, more SLT should be carried out instead.

OR

(B) Statnamic Load Test (sNLT) on Pile:

a. To fulfil the criterion "With explicit verification of SLS", a minimum percentage (%) of constructed piles listed in Table 3 should be subjected to sNLT.(IV)

Note:

(IV) sNLT can be omitted if it is technically not suitable to carry out sNLT on the pile (e.g. bored pile with capacity solely relying on rock socket, etc.). Then, more SLT should be carried out instead. Since the reliability of test results using sNLT lies between SLT and DLT, a higher percentage of tests are need compared to SLT but a lower percentage compared to DLT.

Table 3 Recommended Percentage of Piles to be Tested

Options	**Percentage of Constructed Piles to be Tested to Fulfil Criteria of "*<u>WITH</u>* explicit verification of SLS"**				
	Must Include		**Either**		**Either**
	SLT		**DLT**		**sNLT**
1	> 0.2%	**AND**	> 1.0%	**OR**	≥ 0.5%
2	> 0.1%		> 2.5%		≥ 1.2%
3	> 0.05%		> 5.0%		≥ 2.5%
4*	> 0.3%		NIL		NIL
The following minimum numbers of SLTs should be carried out: 1. Minimum one (1) for total piles < 500. 2. Minimum two (2) for 500 ≤ total piles < 1000. 3. Minimum three (3) for total piles ≥ 1000.					
*Especially for bored/barrette piles with capacity mainly derived from rock socket friction.					

4. CONCLUSION

A general concept for rationalisation of conventional geotechnical practice to EC7 on the design of pile foundations under axial compression load is presented based on Malaysian experience. Some important aspects which should be considered include comparison with local practice on adopted factors of safety, review of pile testing requirements, clear distinction between partial factors on resistance for shaft and base and calibration with actual case histories/load test results.

5. REFERENCES

[1] Chow, C.M. & Tan, Y.C., "Jack-in Pile Design – Malaysian Experience and Design Approach to EC7", IEM Course on Eurocode 7-Geotechnical Design, Kuala Lumpur, July, 2009.

[2] Chow, C.M. & Tan, Y.C., "Performance of Jack-in Pile Foundation in Weathered Granite", Proceedings of 17th SEAGC, Taipei, Taiwan, May, 2010.

[3] Tan, Y.C. & Chow, C.M., "Design & Construction of Bored Pile Foundation", JKR Conference on Pile, Ipoh, Perak, September, 2003.

[4] Tan, Y.C., Wong, S.Y., Lee, C.B. & Gue, S.S., "Comparison of Malaysian Practice with EC7 on the Design of Driven Pile and Bored Pile Foundations under Axial Compression Load", IEM Course on Eurcode 7-Geotechnical Design, Kuala Lumpur, July, 2009.