Rationalised Settlement Criteria for Pile Load Test

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In Malaysia, pile load test settlement criteria are normally based on JKR's Standard Specification for Piling Works. The criteria recommended by JKR are as follows:

A pile tested shall be deemed to have failed if (JKR, 1988):

i. The residual settlement after removal of the test load exceeds 6.50mm
ii. The total settlement under the Working Load exceeds 12.50mm
iii. The total settlement under twice the Working Load exceeds 38.0mm, or 10% of pile diameter/width whichever is the lower value.

The criteria given by JKR have served the industry well since its introduction but the settlement criteria may produce difficulties in situations where relatively long or large diameter piles are adopted. This is because the elastic compression of long or large diameter piles is signficant and very often, the elastic compression recorded during pile testing exceeds the recommended criteria specified by JKR. This may result in unrealistic design if the criteria recommended by JKR are strictly imposed.

In addition, strict adherence to the requirements of total settlement under twice the Working Load not exceeding 38.0mm, or 10% of pile diameter/width whichever is the lower value will also result in unduly conservative pile design. This is because pile is traditionally designed to global Factor of Safety (FOS) of 2.0 which means the pile is expected to fail with excessive settlement much larger than 38mm at twice the Working Load.

Therefore, if the pile settlement under twice the Working Load is within JKR's settlement criteria, it means that the pile FOS is more than 2.0! This also applies similarly to criterion on residual settlement.

In this paper, some comparisons of settlement criteria of other countries and published literatures are made and rationalised settlement criteria for pile testing are proposed based on the on the experiences of the authors and results of recent research.

SETTLEMENT/FAILURE CRITERIA FOR PILE LOAD TESTS

Table 1 summarises some of the settlement/failure criteria for pile load tests from different countries and published literatures extracted from Ng et al. (2004) and which are further updated in this paper by the Authors.

From the table, it can be observed that recent publications have indicated the importance of including pile elastic compression in determining settlement criteria for pile load tests. Some examples include:

a) Federation of Piling Specialists, FPS, UK (2006)
For insensitive buildings:
Pile settlement at DVL, $\Delta M < 10mm + PL/AE$ for piles less than 1000mm diameter.
Where:
P - load on pile
L - pile length
A - cross-sectional area of pile
E - elastic modulus of pile

DVL is the working load plus allowances for soil induced forces such as downdrag or heave, and any particular conditions of the test such as variation of pile head casting level.

For test piles greater than 1000mm diameter a value in excess of 10mm may be appropriate.

Maximum settlement at loads greater than DVL should not be specified for insensitive buildings.

b) Housing Authority, Hong Kong Special Administrative Region (HA)

Pile settlement, $\Delta_M < PL/AE + D/30$ (in mm) $\Delta R^f < D/50$ or 10mm whichever is smaller $\Delta R^b < D/100$ or 5mm whichever is smaller where ΔR^f is the residual settlement for pile embedded in soil, ΔR^b is the residual settlement for pile bearing on rock.

Furthermore, BS8004: 1986, Clause 7.5.6.5 also highlights that the ultimate bearing capacity of the pile may be taken as the force at which the penetration is equal to 10% of the diameter of the base of the pile but elastic shortening will need to be taken into account for very long piles. This is because the elastic shortening of the long pile itself may reach 10% of the base diameter.

As such, from a review of current practices worldwide, it is demonstrated that there is a need for Malaysian settlement criteria for pile load tests be updated.

PROPOSED SETTLEMENT CRITERIA FOR PILE LOAD TEST – BORED PILES

The proposed settlement criteria for pile load test for bored piles are based on Ng et al. (2004) where test piles range from 0.6 to 1.8m in diameter and from 12 to 66m in length are used in establishing the proposed criteria.

STUDY OF PILE TOE MOVEMENT FOR BORED PILES

In order to establish suitable settlement criteria for failure load, studies on the toe resistance-movement relationships have been carried out and the results are summarised in **Figure 1**. From **Figure 1**, it can be seen that the full mobilisation of toe resistance is difficult to achieve, as it may require extremely large toe movements. However, a moderately conservative movement for the mobilisation of toe resistance has been identified to be 4.5% of pile diameter (d), and this is consistent for both piles founded on residual soils and piles founded on weathered rocks (Ng et al. (2004)).

STUDY OF SHAFT SHORTENING FOR BORED PILES

In some of the settlement criteria summarised in Table 1 (e.g. Davisson criteria and FPS Method), pile shaft shortening equal to PL/AE is included in determining allowable settlement. The assumption made is that no frictional resistance acts along the whole pile length. However, the magnitude of pile shaft elastic shortening is less than PL/AE due to resistance from the soil. Measurement carried out by Ng et al. (2001) – Figure 2 shows

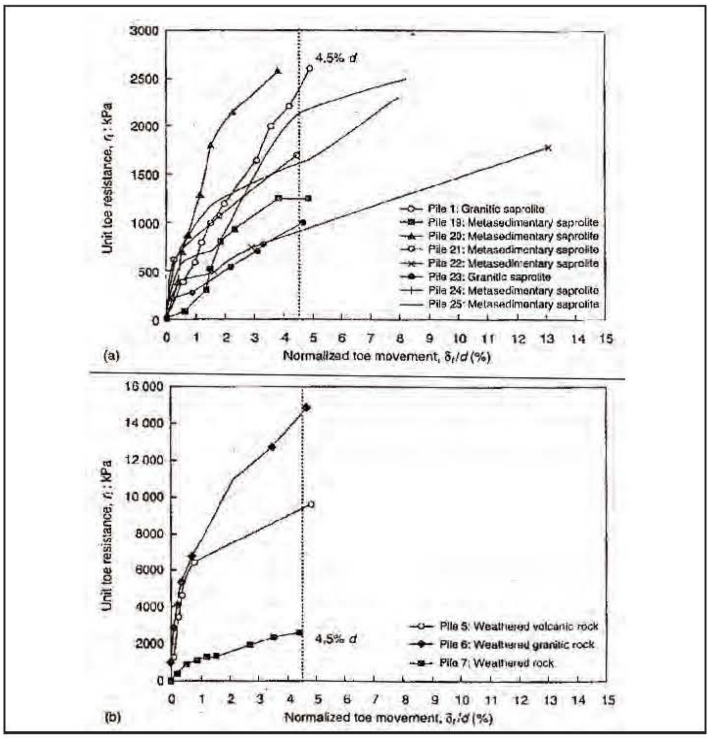

Figure 1: Toe resistance-movement relationships for (a) piles embedded in saprolites; (b) piles socketed in and founded on weak rocks (after Ng et al., 2001).

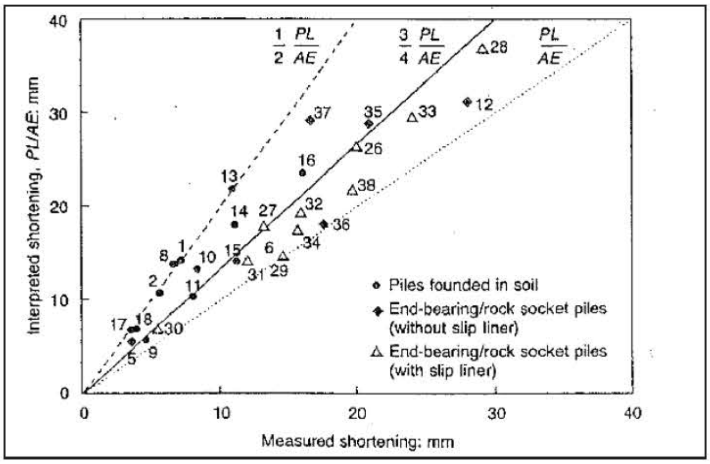

Figure 2: Pile shaft shortening (after Ng et al., 2001).

that the elastic compression is less than PL/AE and a moderately conservative estimate of shaft shortening are as follows:

a) For piles founded in soil,
   Elastic shortening = ½ PL/AE
b) For piles founded on rocks and/or with rock sockets and for piles with slip liners Elastic
   shortening = ¾ PL/AE

In order to propose appropriate settlement criteria for pile load test of bored piles, the design approach generally adopted in Malaysia for design of bored piles is briefly discussed below.

DESIGN OF BORED PILES – MALAYSIAN PRACTICE (TAN & CHOW, 2003)

In conventional bored pile design practiced in Malaysia, the Factors of Safety (FoS) normally used in static evaluation of pile geotechnical capacity are partial FoS on shaft (Fs) and base (Fb) respectively; and global FoS (Fg) on total capacity. The lower geotechnical capacity obtained from both methods is adopted as allowable geotechnical capacity

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

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

Note: Use the lower of Qag obtained from eq. 1 and eq. 2 above. BS8004:1986, Clause 7.3.8 also states that:

"In general, an appropriate Factor of Safety for a single pile would be between two and three. Low values within this range may be applied where the ultimate bearing capacity has been determined by a sufficient number of loadings tests or where they may be justified by local experience…"

Similarly, American Society of Civil Engineers (ASCE), 1993 also recommends a minimum global factor of safety of 2.0 for compression pile where the pile capacity is verified by a sufficient number of load tests on preliminary piles.

Where:

Q_{ag}	=	Allowable geotechnical capacity (has not included down-drag force, if any)
Q_{su}	=	Ultimate shaft capacity = $\sum_i (f_{su} \times A_S)$
i	=	Number of soil layers
Q_{bu}	=	Ultimate base capacity = $f_{bu}\, A_b$
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 = 1.5
F_b	=	Partial Factor of Safety for Base Resistance > 3.0
F_g	=	Global Factor of Safety for Total Resistance (Base + Shaft) = 2.0

As such, bored piles are commonly designed to global FOS of 2.0. Therefore, it is acceptable for bored piles to fail when tested to twice the Working Load. Limiting the settlement criteria at twice the Working Load is therefore irrational and leads to unduly conservative design.

CRITERIA ON RESIDUAL SETTLEMENT

Residual settlement criteria as adopted in JKR's Standard Specification for Piling Works should be reviewed based on the following discussion. Although the residual pile movement may give some indication of soil yield along the shaft and at the pile tip, the magnitude of residual settlement is strongly affected by 'locked-in movement' of the pile. This is because the anticipated elastic rebound of the pile may be affected by side shear acting downward against the pile unloading and preventing it from fully recovering the elastic compression.

This locked-in effect cannot be accurately and reliably assessed (Ng et al., 2004). In addition, the residual movement is affected by any creep in the concrete pile. These two phenomena are likely to be more prominent in long and large-diameter bored piles and barrettes than short and small-diameter driven piles (GEO, 1996; Ng et al., 2001). The residual pile movement criterion is therefore irrational, unreliable and unsuitable for use as an acceptance criterion, especially for long piles and barrettes, and it always leads to unnecessarily conservative design (GEO, 1996).

TEST LOAD FOR WORKING PILES

For working piles, it is adequate to test the pile up to 1.5 times instead of 2.0 times the Working Load. This is to prevent damaging the working piles and is consistent with the recommendations of ICE Specification for Piling and Embedded Retaining Walls (ICE, 2007) where proof test (equivalent to working pile test) is required to be tested up to 100% DVL + 50% SWL which is equivalent to 1.5 times the Working Load for piles not subjected to downdrag. (Note: Design Verification Load, DVL – working load plus allowances for soil induced forces such as downdrag or heave, and any particular conditions of the test such as variation of pile head casting level, SWL – specified working load).

Therefore, the proposed settlement criteria for pile load test for bored piles are as follows:

a) The total settlement at Working Load does not exceed the following magnitude or other suitable magnitude based on structural considerations:

For piles founded in soils:

$$\Delta_M = 12.50\text{mm} + \tfrac{1}{2}\, PL/AE$$

For piles founded on rocks and/or with short rock sockets and for piles with slip liners:

$$\Delta_M = 12.50\text{mm} + \tfrac{3}{4}\, PL/AE$$

Note: The 12.50mm limit is a conservative limit to ensure that differential settlement between columns of a building will not affect its safety and serviceability. Typically, differential settlement between any two piled foundations is unlikely to be greater than 75% of the maximum settlement (Craig, 1998). As such, for medium-rise to high-rise buildings with column spans ranging from 5.0m to 8.5m where bored piles are typically used, the maximum differential settlement for a 25m long, 1.2m diameter rock-socketed bored pile (Working load = 9800kN) would be approximately equal to 0.75*18.5mm = 14mm.

The distortions due to the differential settlement will range from 1/350 to 1/600 which is within the allowable limits to prevent cracking in walls and partitions of 1/300 and well within the limits for structural damage of 1/150 (Skempton & McDonald, 1956). In the design of foundations, it is important to control distortions/ differential settlement rather than total settlement. Controlling total settlement in order to reduce distortions/differential settlement will lead to unduly conservative design. Understanding this principle will produce better foundation design and is consistent with international practice where total settlement of high-rise buildings exceeding 100mm has been reported.

Some recorded total settlement of high-rise buildings of more than 40-storey in Germany is shown in Figure 3.

b) The total settlement, at 1.5 times the Working Load, does not exceed the following values:

For piles founded in soils:

$$\Delta_M = 0.045d + \tfrac{1}{2}\, PL/AE$$

For piles founded on rocks and/or with short rock sockets and for piles with slip liners:

$$\Delta_M = 0.045d + \tfrac{3}{4}\, PL/AE$$

where d is the pile diameter/size.

Note: The above values were also proposed by Ng et al. (2004) as failure load criterion for large diameter bored piles and barrettes. The 0.045d limit is based on a moderately conservative movement for the mobiliszation of toe resistance (refer to Figure 1).

Criteria on settlement at twice the Working Load and residual settlement are omitted based on the technical justifications discussed earlier. In addition, the test load for pile testing shall be as follows:

a) Working piles – tested up to 1.5 times the Working Load
b) Preliminary piles – tested up to at least 2.0 times the Working Load or until the test load cannot be sustained.

Figures 4 and 5 illustrate the difference between JKR's criteria and the proposed criteria for bored piles founded on rock.

Notes:

1. Figure derived using 1200mm diameter bored pile founded on rock
2. Bored pile constructed using Grade 35 concrete.
4. Pile working load = 9800kN.
5. Pile working load is assumed equal to structural capacity of pile.

Notes:

1. Figure derived based on pile length of 25m founded on rock.
2. Bored pile constructed using Grade 35 concrete.
3. Pile working load is assumed equal to structural capacity of pile.

As can be seen from Figures 4 and 5, the proposed criteria are similar to existing JKR criteria for small pile diameter and relatively short pile length. However, with increasing pile length and diameter, the proposed criteria give more rational settlement criteria and will not result in overly conservative design.

PROPOSED SETTLEMENT CRITERIA FOR PILE LOAD TEST – DRIVEN PILES

Based on experience and findings on bored piles, the settlement criteria for pile load test for driven piles is proposed based on similar concept. The difference in load-transfer mechanism between driven piles and bored piles can generally be summarised as follows:

a) **Magnitude of shaft friction**

The mobilised shaft friction for driven piles is expected to be higher compared to bored piles due to soil displacement during pile installation.

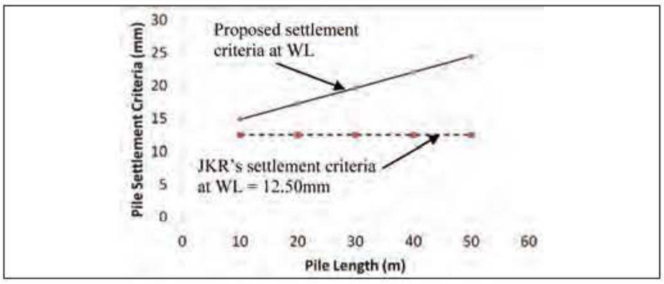

Figure 4: Effect of pile length on pile settlement criteria.

b) **Mobilisation of end-bearing resistance**

The required pile settlement in order to mobilise end-bearing resistance for driven piles is expected to be smaller compared to bored piles due to compression of soil at pile tip during installation and effect of residual load due to locked-in effect during pile installation.

As such, the proposed settlement criteria for pile load test for driven piles are as follows:

a) The total settlement at Working Load does not exceed the following magnitude or other suitable magnitude based on structural considerations:

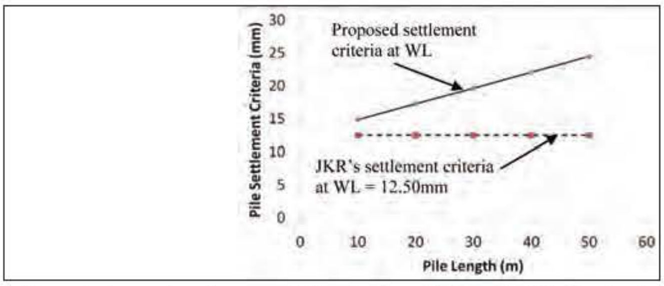

Figure 5: Comparison between JKR's criteria at 2.0 times the Working Load with proposed criteria at 1.5 times the Working Load.

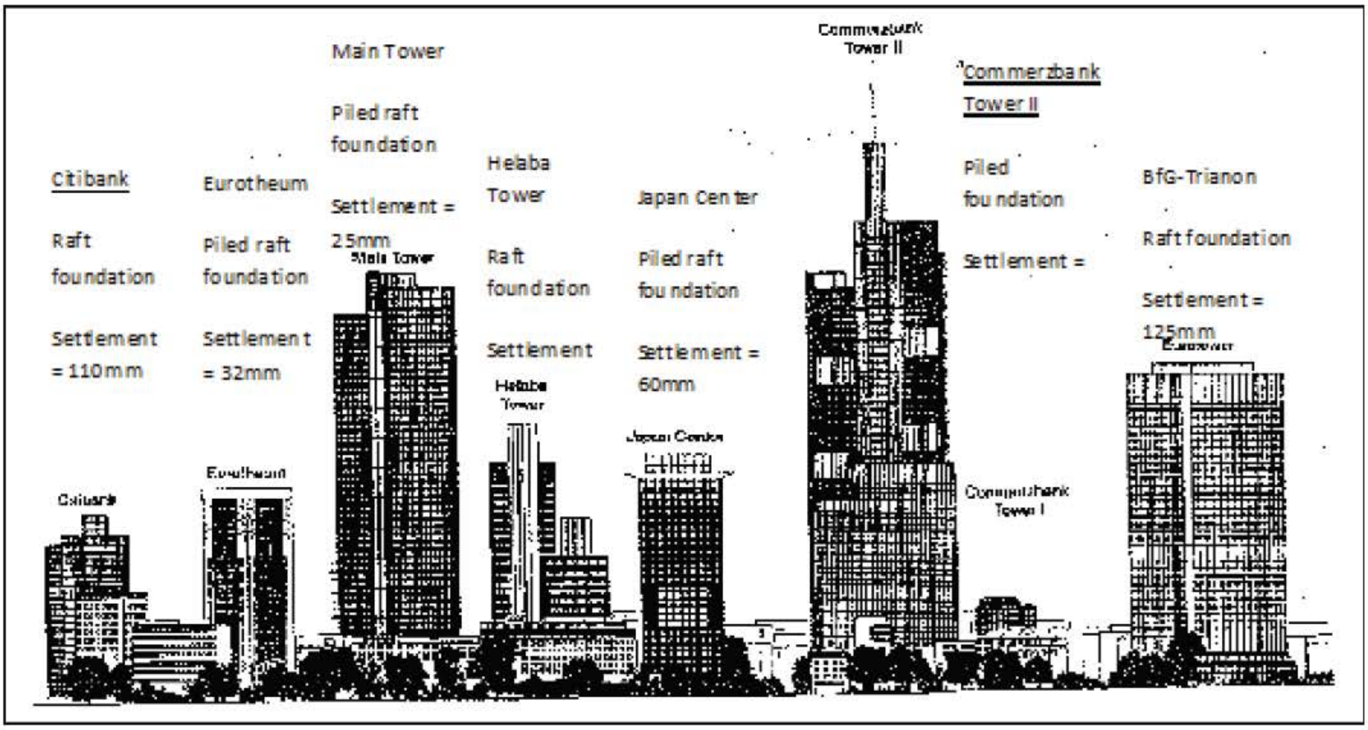

Figure 3: Observed settlement of buildings in Germany (after Katzenbach et al., 2000 and Franke et al., 2000)

For piles founded in soils and rocks:

Δ_M = d/120 + PL/AE + 4.0mm

Notes:

1. The abovecriteria are similar to Davisson (1972) which is widely adopted.
2. The component for elastic compression used is similar to bored piles. However, the actual magnitude of elastic compression is expected to be even smaller compared to bored piles. This is because the shaft friction in driven piles is expected to be higher and so, the elastic compression is reduced due to resistance from shaft friction.
3. The criteria d/120 is consistent with experience in dynamic testing of piles, which is the recommended toe quake, i.e. displacement at which the static soil resistance changes from elastic to plastic behaviour (Goble & Rausche, 1986)).
4. The magnitude of 4.0mm is consistent with the recommendations of Davisson, 1972.

b) The total settlement at 1.5 times the Working Load does not exceed the following values:

For piles founded in soils and rocks:

Notes:

1. The above criteria is based on the assumption that the pile has "failed" when pile top settlement equal to 10% of the pile base diameter which is specified in BS8004 and Eurocode 7.
2. Only half of the elastic shortening component (PL/AE) is conservatively included in the proposed criteria. This is to account for load transfer mechanism which will reduce the elastic shortening of the pile.

Figures 6 and 7 illustrate the difference between JKR's criteria and the proposed criteria for driven piles in soil.

Notes:

1. Figure derived using 200mm x 200mm RC Square pile with Grade 45 concrete.
2. Pile working load = 450kN

Similar to bored piles, from Figures 6 and 7, it can be seen that the proposed criteria give more realistic settlement criteria especially for long piles exceeding 20m.

SUMMARY

Based on latest international practice, recent research carried out and Malaysian practice in piled foundation design, the following settlement criteria for pile load test are proposed:

a) BORED PILES

The total settlement at Working Load does not exceed the following magnitude or other suitable magnitude based on structural considerations:

For piles founded in soils:

Δ_M = 12.50mm + ½ PL/AE

For piles founded on rocks and/or with short rock sockets and for piles with slip liners: Δ_M = 12.50mm + ¾ PL/AE

The total settlement at 1.5 times the Working Load does not exceed the following values:

For piles founded in soils:

Δ_M = 0.045d + ½ PL/AE

For piles founded on rocks and/or with short rock sockets and for piles with slip liners:

Δ_M = 0.045d + ¾ PL/AE

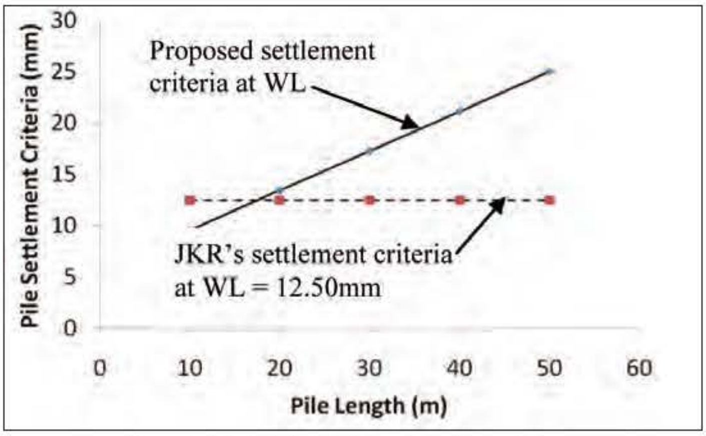

Figure 6: Effect of pile length on pile settlement criteria.

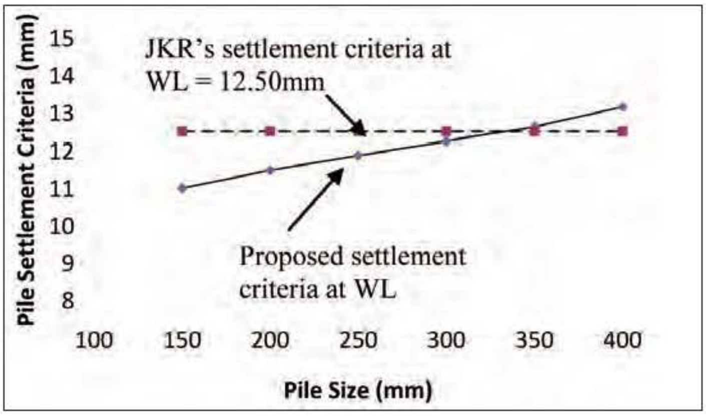

Figure 7: Effect of pile size on pile settlement criteria.
(Note: Figure derived based on RC square pile with pile length of 15m).

b) DRIVEN PILES

The total settlement at Working Load does not exceed the following magnitude or other suitable magnitude based on structural considerations:

For piles founded in soils and rocks:

ΔM = d/120 + PL/AE + 4.0mm

The total settlement at 1.5 times the Working Load does not exceed the following values:

For piles founded in soils and rocks:

ΔM = 0.1d + ½ PL/AE

The settlement criteria for driven piles can be further refined as there is still some degree of empiricism in the proposed criteria (e.g. 4.0mm value). Further research can be carried out on driven piles to determine more realistic elastic compression of the pile taking into consideration the effect of load transfer to facilitate refinement of the settlement criteria.

Criteria on settlement at twice the Working Load and residual settlement are omitted based on the technical justifications discussed above. In addition, the test load for pile testing shall be as follows:

a) Working piles – tested up to 1.5 times the Working Load
b) Preliminary piles – tested up to at least 2.0 times the Working Load or until the test load cannot be sustained.

The proposed settlement criteria are based on technical justifications to prevent unduly conservative design and are consistent with international geotechnical practice. ■