A Critical Review of Pile Acceptance Criteria

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ABSTRACT

Pile acceptance criteria previously or currently used in Hong Kong by the Buildings Department, Housing Department, Architectural Services Department and the Civil Engineering and Development Department are reviewed. It is observed that the pile acceptance criteria are mainly aimed at controlling the settlement of piles. Some of the acceptance criteria used for total settlement or residual settlement are not reasonable and excessively restrictive. A proposal involving simplification of the Davisson criterion and removal of the residual settlement criteria is presented for unifying the current pile acceptance criteria in Hong Kong.

1. INTRODUCTION

Pile loading tests are commonly used for obtaining or verifying the parameters of pile design or as a means of compliance testing for ascertaining whether a batch of completed piles will meet with the design standard or requirements. A set of pile acceptance criteria is often stipulated to decide whether a test pile will pass the loading test. Pile acceptance criteria used for loading tests in Hong Kong evolve with time and vary between departments. A review of the past and current acceptance criteria for pile loading tests in Hong Kong is presented and a proposal for simplifying the pile acceptance criteria will also be discussed.

2 HISTORICAL DEVELOPMENT

Over the years, various government departments in Hong Kong, including Buildings Department (BD), Housing Department (HD), Architectural Services Department (ASD) and Civil Engineering and Development Department (CEDD), have developed their own acceptance criteria for assessing whether a test pile would be satisfactory based on the results of a static loading test. The pile acceptance criteria adopted by the BD, ASD and HD are becoming almost identical in recent years. Table 1 summarizes the pile acceptance criteria that have been used by the four departments.

In the following, the evolution of pile acceptance criteria implemented by the above government departments will be briefly reviewed. The review is by no means comprehensive due to difficulties in tracing all the changes that have been made as past information on old pile acceptance criteria is not readily available in the public domain.

Table 1: Summary of pile acceptance criteria adopted by various government departments

Department	Total settlement criterion, δ_{max}	Residual settlement criterion, δ_r	Time	Reference
BD	0.5 inches	-	Prior to 1976	Philcox (1962a, 1962b)
	15mm	-	1976 to late 1980s	HKG (1976), LHK (1985)
	$\delta_{max} = \frac{P \times L}{A \times E} + \frac{D}{120} + 4$	$\delta_r = \frac{D}{120} + 4$	Late 1980s to 2004	Fraser & Ng (1990)
	$\delta_{max} = \frac{P \times L}{A \times E} + \frac{D}{120} + 4$	$\delta_r = \frac{D}{120} + 4$ or $\frac{1}{4}\delta_{max\_observed}$ whichever is larger	After 2004	BD (2004, 2017)
ASD	$\delta_{max} = 0.7\frac{P \times L}{A \times E} + \frac{D}{120} + 4$	$\delta_r = \frac{D}{120} + 4$	Between 1993 to 2003	ASD (1993)
	$\delta_{max} = \frac{P \times L}{A \times E} + \frac{D}{120} + 4$	$\delta_r = \frac{D}{120} + 4$	After 2003	ASD (2003)

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	$\delta_{max} = \frac{P \times L}{A \times E} + \frac{D}{120} + 4$	$\delta_r = \frac{D}{120} + 4$ or $\frac{1}{4}\delta_{max\_observed}$ whichever is larger		ASD (2007)
HD	$\delta_{max} = \frac{P \times L}{A \times E} + \frac{D}{30}$	$\delta_r = \frac{D}{50}$ or 10mm, whichever is less for floating pile $\delta_r = \frac{D}{100}$ or 5mm, whichever is less for end-bearing pile		HKHA (1989), Yiu & Lam (1990)
	$\delta_{max} = \frac{P \times L}{A \times E} + \frac{D}{120} + 4$	$\delta_r = \frac{D}{120} + 4$	Since formation of ICU in 2002 to 2004	
	$\delta_{max} = \frac{P \times L}{A \times E} + \frac{D}{120} + 4$	$\delta_r = \frac{D}{120} + 4$ or $\frac{1}{4}\delta_{max\_observed}$ whichever is larger	After release of CoPF in 2004	
CEDD	(a) Brinch Hansen criterion (b) $\delta_{max} \leq$ 20mm for buildings and 15mm for other structures	-	Since 1992	CEDD (1992)

2.1 Buildings Department

The BD originated from the Buildings Ordinance Office (BOO) of the former Public Works Department (PWD). The BOO became the Building Development Department (BDD) from 1982 to 1986, the Buildings and Lands Department (BLD) from 1986 to 1993 before becoming the BD after 1993. In this paper, the BD will also collectively mean the BOO, BDD and BLD.

Up to the late 1970s, the pile acceptance criterion adopted by the BD was simple and based entirely on a total settlement limit of ½ inches when tested under twice the design working load as discussed by Philcox (1962a, 1962b). The total settlement limit was later revised to 15mm and formally incorporated as a legal requirement in the Building (Construction) Regulations (B(C)R) (HKG 1976) and this criterion was still present in the 1985 edition of B(C)R (LHK 1985). There was no residual settlement criterion at the time.

As remarked by Philcox (1962a), if the settlement for a single pile is limited to ½ inches (or about 15mm), the total settlement of a tall building was expected to be within 2 inches (or 50.8mm) and considered to be acceptable. The pile acceptance criterion of a constant settlement limit adopted by the BD up to the late 1980s was simply an indirect tool for ensuring that the building settlement is acceptably smaller, and not a guideline for assessing of the ultimate capacity of the test pile.

In the late 1980s, the simple pile acceptance criterion of a constant total settlement limit was removed from the B(C)R and revised pile acceptance criteria were specified in Practice Note No.66 issued by the BD to building professionals as follows (Fraser & Ng 1990).

$$\delta_{max} = \delta_e + \delta_{tip} = \frac{P \times L}{A \times E} + \frac{D}{120} + 4 \quad (1)$$

$$\delta_r = \delta_{tip} = \frac{D}{120} + 4 \quad (2)$$

where P = maximum test load at design failure load equal to twice the design working capacity in kN; δ_{max} = settlement in mm at maximum test load P; δ_r = residual settlement in mm upon complete release of test load; L, A, E and D are the length in mm, cross-sectional area in mm^2, Young's modulus in kN/mm^2 and D the lateral dimension in mm of the pile respectively. Eq.1 and 2 will hereafter be called the total and residual settlement criterion respectively.

The total settlement criterion of Eq.1 is commonly referred to as the Davisson criterion because it is adapted from the proposal by Davisson (1972). It consists of a component δ_e representing the pile shortening and another term δ_{tip} related to the pile tip movement that will cause yielding of soils at the base. Theoretically, the pile shortening δ_e can be characterized by a coefficient α as follows.

$$\delta_e = \int_0^L \frac{P_A(z)}{A\times E}\,\mathrm{d}z = \alpha\,\frac{P\times L}{A\times E} \tag{3}$$

where $P_A(z)$ is the variation of axial load of pile with depth z. According to Davisson (1972), the component δ_e in the total settlement criterion can be obtained by treating the pile as a free column without shaft resistance. This corresponds to $P_A(z) = P$ and $\alpha = 1$. The expression for δ_{tip} in Eq.1 is suggested by Davisson based on his own experience. There is no data presented by Davisson (1972) or others for confirming the appropriateness of this expression. There was no residual settlement criterion proposed by Davisson (1972).

The residual settlement criterion of Eq.2 was introduced only by the BD and the settlement limit used in equation is the same as the pile tip settlement δ_{tip} in the Davisson criterion. This seems to suggest that the BD would regard the pile shortening to be fully elastic and recoverable and not for the pile tip movement. As it turns out, the residual settlement criterion introduced by the BD is extremely stringent. Test piles would often fail due to inability to satisfy the residual settlement criterion.

In 2004, the BD published the Code of Practice for Foundations (CoPF) (BD 2004) in which the residual settlement criterion was revised as follows, keeping the total settlement criterion unchanged.

$$\delta_r = \frac{D}{120} + 4 \quad \text{or} \quad \frac{1}{4}\delta_{max\_observed}\text{, whichever is larger} \tag{4}$$

where $\delta_{max\_observed}$ is the observed total settlement at maximum test load. Since then, the BD pile acceptance criteria has remained unchanged in the later edition of CoPF released in 2017 (BD 2017) and subsequent amendments of the code promulgated released between 2021 and 2023.

2.2 Architectural Services Department

The ASD originated from the Architectural Office of the PWD and was formally established as a department in 1986. The pile acceptance criteria adopted by the ASD are promulgated in the General Specification for Building (GSB) published by the Department. Over the years, the acceptance criteria for total and residual settlement adopted by the ASD have the same format as those of the BD as summarized in Table 1, except for the differences mentioned below.

a. In the 1993 edition of GSB (ASD 1993), the total settlement criterion is based on a value of α equal to 0.7, resulting in a significantly more stringent criterion than that of the BD at the time.
b. In the 2003 edition of the GSB (ASD 2003), the coefficient α is revised to 1.0 and the total settlement criterion then became the same as that of the BD at the time.
c. In 2007, the ASD further revised the residual settlement criterion to match with that of the CoPF 2004 Edition (ASD 2007).
d. Over the years, the definitions of the pile dimension D used by the ASD are slightly different from those of the BD for certain pile types, although the differences have become smaller with time.

With the above evolution, the pile acceptance criteria currently adopted by the ASD are now identical to those of the BD, except for the definition of D for a certain pile type.

2.3 Housing Department

The formats of the pile acceptance criteria adopted by the HD are also similar to those of the BD. In an early version of the HD pile acceptance criteria used in the late 1980s (see Table 1), the pile shortening δ_e in the total settlement criterion was based on $\alpha = 1$ and the pile tip movement δ_{tip} was defined somewhat differently as $D/30$. The residual settlement criterion used by the HD at the time was specified as $\delta_r = D/50$ or 10mm, whichever is less, for normal designs and reduced to $\delta_r = D/100$ or 5mm for piles founding on rock if the group reduction factor is not used for foundation design. The definition of D used by the HD at that time also differed from that of the BD for some pile types.

In 2002, the Independent Checking Unit (ICU) was established within the HD to perform independent administrative building control over housing development projects of the Department according to the requirements implemented by the BD (HKHA 2020). Since then, the pile acceptance criteria used by the HD are identical to those of the BD.

2.4 Civil Engineering and Development Department

The pile acceptance criteria adopted by CEDD are described in the General Specification for Civil Engineering Works published by the Department. The Specification was first published in 1992 (CEDD, 1992). The pile acceptance criteria in it have since remained unchanged in subsequent amendments and new editions of the Specification. The pile acceptance criteria are based on the Brinch Hansen criterion, with the pile settlement at working load restricted to no more than 20mm for buildings and 10mm for other structures.

The Brinch Hansen criterion was originally a method developed by Brinch Hansen (1963, 1965) for assessing the failure stress of a soil from its stress-strain curve, not for establishing the failure loads of piles. There are actually two methods proposed by Brinch Hansen, commonly known in the literature as the 90% criterion and the 80% criterion. The former is defined as the stress for which the strain is 2 times the strain at a 10% smaller stress. Brinch Hansen (1965) considers that his two proposed methods should also be applicable to almost any test, including pile loading tests, although there is no data presented in his paper for justifying this assertion. It is perhaps for this remark by Brinch Hansen that the 90% or 80% criterion has now been borrowed by others, including Fellenius (1989), Dotson (2013) and also the CEDD, for estimating the ultimate failure load of a test pile. The Brinch Hansen criterion used by CEDD is actually the 90% criterion.

The pile acceptance criteria adopted by the CEDD are more stringent than just the checking of the ultimate capacity of pile using the Brinch Hansen criterion. For the test pile to pass the acceptance criteria, the pile settlement at working load must also fulfill the additional requirement of a small settlement mentioned above.

3 REVIEW ON PAST AND CURRENT PILE ACCEPTANCE CRITERIA

The acceptance criteria implemented by various government departments in Hong Kong aim at controlling the performance of piles through imposing acceptance criteria for total settlement at maximum test load, residual settlement after full release of test load and/or limiting the settlement at working load. Before discussing possible simplifications to current procedures, it is useful to review the above strategies that have been adopted in formulation of past and current pile acceptance criteria.

3.1 Total settlement criterion based on constant settlement limit

The use of a constant limit for pile settlement under working load or at maximum test load is a very simple strategy for controlling the performance of piles. The use of a constant settlement limit of ½ inches or 15mm by the BD in the past for the total settlement at maximum test load and the limitation of pile settlement by the CEDD to within 20mm or 10mm at working load are good examples of such a simple approach. Unfortunately, these settlement limits are small and even more stringent than the value of 30mm recommended by the BD in the CoPF (BD 2017) for footings on soils. As remarked very early by Lumb (1962), "most tall buildings in Hong Kong have settled a few inches, unless founded on rock, although such settlements are not very noticeable". Lumb further commented that "probably for tall stiff buildings a total settlement of 2 inches would not be any cause for alarm".

From a technical point of view, it is not rational to adopt a pile acceptance criterion based on a constant settlement limit because pile settlement is larger for piles with a higher strength capable of resisting a higher foundation load and also increases with the pile length due to shortening under loading. For long piles with length exceeding 50m, which are not uncommon in Hong Kong, the pile settlement under working load can easily exceed 20mm according to loading test data presented by Zhang & Yu (2005). Capping the maximum pile settlement at 20mm or less is unreasonably conservative.

A total settlement criterion based on a constant settlement limit may be made more sensible by specifying multiple settlement limits for different ranges of pile lengths or applied load, but this will defeat the very purpose of keeping the approach simple.

3.2 Total settlement criterion based on load-settlement curve

The total settlement criteria currently adopted by the BD, HD, ASD and CEDD all involve assessment of the failure load from the load-settlement curve.

The Brinch Hansen criterion, being originally developed for estimating the failure stress of soils at high strain level, will tend to predict the failure pile load at a point on the load-settlement curve where the settlement starts to plunge. The corresponding settlement at the predicted failure load may be too high to be used as a suitable total settlement criterion. One will have to resort to another means for setting a suitable settlement limit to control pile movement, such as limiting the settlement at the working load as has been adopted by CEDD.

From experience, the Davisson criterion for total settlement is relatively conservative and the failure load of the pile so determined will be not be close to reaching ultimate failure. A similar observation is also made by Fraser & Ng (1990). In a case study reported by Fellenius (1980), the failure load inferred from the Brinch Hansion 90% criterion is found to be 13% higher than that obtained by the Davisson criterion.

When formulating a suitable total settlement criterion, pile shortening should be duly considered. The magnitude of α depends on shaft resistance which is affected by many factors including pile type, details and method of installation, soil profile and others.

For driven and jacked H-piles, voids will be formed on both sides of the web of the H-pile when installed by driving or jacking (Li et al 2003a, 2003b, Tomlinson 1977). Such voids may be as deep as 10m (Li et al 2003b). Even if these voids are backfilled with soils after pile installation, the backfilled materials are likely to be loose resulting in low shaft resistance below the pile head. Friction fatigue of soils can also occur due to repeated cyclic shearing of soils during pile installation (White & Lehane 2004). This will result in higher reduction in shaft resistance at depths nearer to the pile top where the soils will be subjected to more cycles of shearing.

When piles are installed through soft soils, such as marine deposit commonly present in reclamation sites in Hong Kong, the shaft resistance in the soft soil layers will be low. There are also some mind-boggling foundation practices in Hong Kong that can contribute to low shaft resistance. Sleeving of piles is common in Hong Kong to avoid transfer of lateral loads onto adjacent slopes by eliminating shaft resistance in the sleeved zone. Debonding of piles is also common to avoid transfer of vertical loads from spreading onto adjacent sensitive structure, such as Mass Transit Railway structures or tunnels. Debonding is usually by means of sleeving or coating the pile with a bituminous material. The shaft friction in the debonding zone will then be removed.

If the variation of axial load with depth is known, the coefficient α can be computed using Eq.3. For driven piles, such information can be obtained from CAPWAP analysis of the data obtained from a PDA test. Figure 1 shows the variation of axial load obtained by CAPWAP analysis for six driven H-piles installed at a reclamation site in Kowloon. The axial load presented in the figure is normalized by the maximum test load. The soil profile of the site comprises a stratigraphic sequence of fill, a thin layer of marine deposit, alluvial deposit and finally the founding stratum of completely decomposed granite.

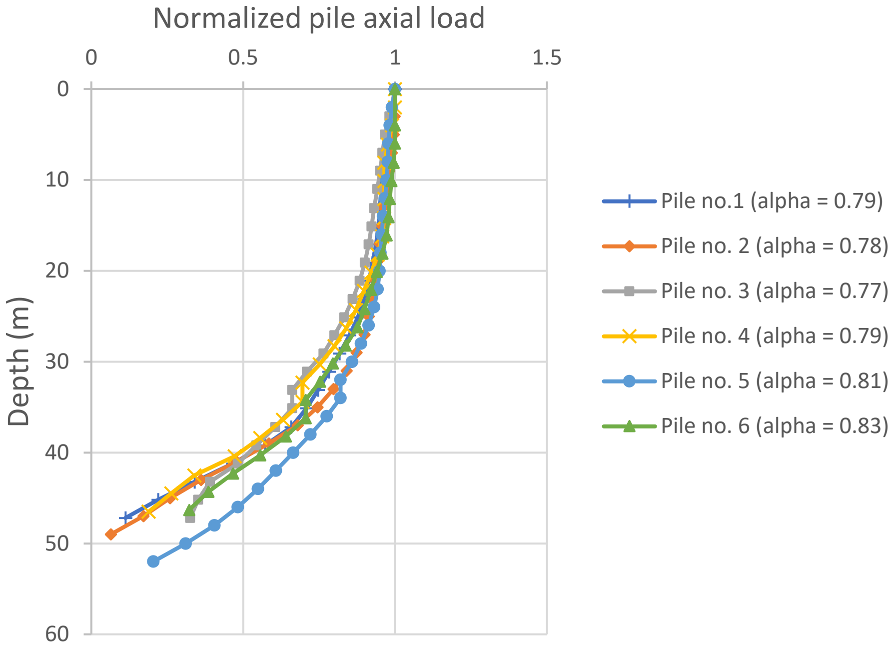

Figure 1: Variation of axial loads of driven piles estimated by CAPWAP analysis

The decrease in axial pile load is slow in the upper portion of the pile, indicating that the shaft resistance is more significant only at the lower part of the pile. The values of α for these 6 piles calculated using Eq.3 range from 0.77 to 0.83. For driven piles installed in a reclamation site with a thick marine deposit, the value of α is expected to be even closer than 1.0. If the 1993 version of the ASD total settlement criterion based on $\alpha = 0.7$ were to be adopted as the acceptance criterion, it will be difficult even for well performing driven piles to pass the loading test.

The total settlement criterion adopted currently by the BD, ASD and HD all contain a component related to the pile tip movement equal to $\delta_{tip} = D/120 + 4$. For the common pile types in Hong Kong, the magnitude of this term is small and generally in the range of about 6.7 to 8mm. According to the CoPF, loading tests are used for proof testing of piles only for piles with lateral dimension not exceeding 750mm. Even for this pile size, the magnitude of δ_{tip} is 10.25mm which is still considered to be small and unlikely to cause plastic failure of soils at the pile tip.

The Davisson criterion currently adopted by BD, HD and ASD is usually dominated by the term δ_e for pile shortening as the magnitude of δ_{tip} is usually small in comparison. As the observed value of α can be close to 1.0 for driven piles, piles installed in profiles with soft soils, and piles with sleeving or debonding provided, the use of $\alpha = 1$ by Davisson in evaluating the pile shortening is regarded to be a very reasonable and practical recommendation.

3.3 Residual settlement criterion

There was no residual settlement criterion used by the BD prior to the late 1980s and by the CEDD throughout. This residual settlement criterion was only introduced by the BD in the late 1980s in the form of Eq.2 and later modified to Eq.4. The residual settlement criterion introduced by the BD has been followed closely by the HD and ASD. The fundamental question to be asked is whether this additional criterion is sensible or necessary. To answer this question, the author will refer to his viewpoints discussed over 20 years ago in Li et al (2003a).

Figure 2 shows schematically the load-settlement response of a pile supporting a structure. The design capacity of the pile under working load is denoted by WL and the design failure load is 2WL based on a factor of safety of 2.0. Loading on the pile will increase from Point O to Point A due to gradual increase in dead loads and superimposed dead loads during construction. When the structure is finished, there will be further variable live loads and transient wind loads acting on the pile with loads varying between the limits between Point A and B. The loads experienced by the pile will fluctuate along the virgin loading curve defined by Point A and B or the unloading and reloading along the loading curve between A′ and B during the service life of the structure. Full unloading of the pile will not occur like a test pile unless the structure is demolished. It is therefore not meaningful to impose a residual settlement criterion to control the residual movement of an unloaded pile as it has no direct relation to the actual performance of the pile under working condition.

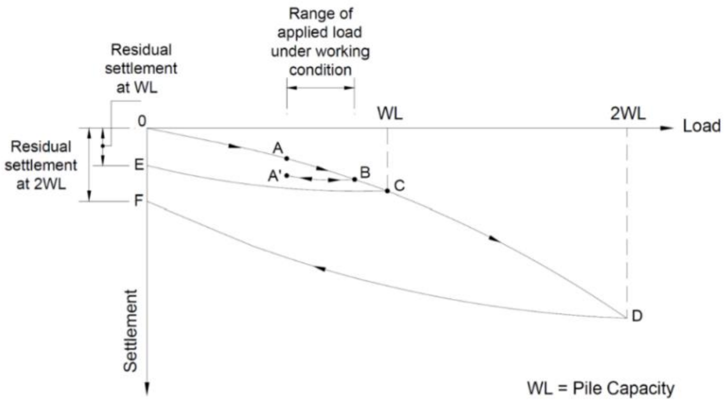

Figure 2 Load-settlement response of a pile foundation supporting a structure (Li et al 2003a)

It may be argued that a small residual settlement criterion is to ensure that the pile will behave elastically for the full range of loading up to 2WL and will therefore serve as an indirect means for ensuring a small pile settlement at working load. If this were indeed the intention of introducing the additional residual settlement criterion, it would be much more meaningful and direct to apply a limit on the settlement of the test pile at working load WL (i.e settlement at Point C) or the residual settlement upon release of test load at WL instead of controlling the residual settlement upon release of maximum test load at the design failure load 2WL.

The BD, HD and ASD had for many years adopted the format of using only the term for the pile tip movement in Eq.2 as the residual settlement criterion, believing that pile shortening should be fully recoverable. This will be demonstrated to be untrue later in the paper.

As the magnitude of δ_{tip} is small and less than 8mm for the common pile types in Hong Kong, the residual settlement criterion is an extremely arduous condition to meet. This is particularly so when the non-recoverable creep settlement which will occur during the 72 hours of maintained loading at maximum test load may itself contribute to a significant percentage of the small residual settlement limit (Lam et al 2021).

The residual settlement criterion has for a long time been the over-riding criterion for pile acceptance, not the total settlement criterion. This has significantly affected the practice of foundation construction in Hong Kong. Driven piles are always driven to a small final set to hopefully produce in a more elastic response of the pile to yield a smaller residual settlement, but this is at the risk of damaging the pile. Jacked piles are preloaded to a load level higher than the design failure load during installation for every pile to ensure that the pile will settle along a loading-reloading path with smaller immediate and creep settlement when load tested (Li 2003b). But preloading of piles will make the foundation design less efficient as the normal full capacity of the pile cannot be used as the design failure load.

Although the residual settlement criterion has been revised to Eq.4 after publication of the CoPF (BD 2004). The revised criterion is only a relaxation compared with Eq.2 for piles with observed total settlement larger than 4 times the magnitude of δ_{tip}. Well performing piles with a smaller total settlement might not be able to benefit from the relaxation and still be unjustifiably rejected. This can be illustrated using a case study in which rock socketed H-piles are used for the foundations. Table 2 summarizes results of loading tests conducted on two piles for the project.

Table 2: Summary of loading test results for two rock socketed H-piles

Pile mark	Pile length (m)	Observed total settlement $\delta_{max-observed}$ (mm)	Observed residual settlement $\delta_{r-observed}$ (mm)
Pile A	30.2	40.6	6.3
Pile B	49.4	35.2	10.3

Pile A is shorter but has a larger total settlement at the maximum test load of about 12200 kN. Pile B is significantly longer but exhibits a smaller total settlement at the same maximum test load. From a technical point of view, Pile B has a better performance than Pile A because it has a smaller total settlement despite its longer length. This is a direct indication that there is significant shaft resistance along Pile B to result in a smaller pile shortening (i.e. a smaller α) and total settlement than Pile A. Unfortunately, the total settlement of Pile B is too small to enable the residual settlement limit to be increased. In the end, the pile cannot pass the BD residual settlement criterion.

It has long been recognized that the residual settlement of a test pile is influenced by the residual load in the pile after loading test or pile installation (e.g. Fellenius 2015; Zhang & Wang 2007). Positive shaft resistance (PSF) will be mobilized along the pile when it is loaded during the loading test. When the test load is released, the pile head will rebound and shaft resistance at the top portion of the pile will reverse in direction causing negative shaft friction (NSF) to develop. PSF and NSF will both lead to the development of residual loads along the pile upon full release of test load, resulting in associated residual settlement after the loading test. If shaft resistance along the pile is significant, the residual settlement may be too large to satisfy the residual settlement criterion.

An approach based on simplifying assumptions has been developed in the Appendix for estimating the residual settlement of Pile B due to residual load. The residual settlement is predicted to be 10.3mm which happens to be the same as the observed value. While the analysis presented in the Appendix may be regarded as oversimplified and the good prediction is perhaps a coincidence, it serves to demonstrate that the residual settlement criterion currently used by BD, HD and ASD can cause a well performing pile to be unreasonably rejected.

For rock-socketed H-piles, there is another cause of residual load that is not normally recognized by foundation engineers. The bond resistance between the plain surface of H-pile and cement grout may not be sufficient to prevent bond slip at the steel-cement grout interface during a loading test (Li 2007). If bond slip does occur during loading, a gap may be formed between the cement gap and the H-pile for some distance below the pile head. When the applied load is released, the gap may close up and the cement grout will inhibit rebound of the H-pile. This will also contribute to development of residual load in the pile and therefore residual settlement.

4 DISCUSIONS AND CONCLUSION

The pile acceptance criteria adopted previously or currently by various government departments are largely aimed at controlling the settlement of piles and not so much at obtaining a reliable estimate of the ultimate capacity of piles. From experience, the ultimate capacity of piles is usually far from being reached if they can comply fully all the pile acceptance criteria. When considering the objectives to be fulfilled when setting the pile acceptance criteria, the following factors should be considered.

a. The criteria should be technically sound or reasonable.
b. The criteria are applicable to a wide range of pile types.
c. The criteria are suitably conservative.

To some extent, the three objectives are in conflict with each other. Objective (b) and (c) are always preferable because they can make regulatory control easier, but one must balance the benefit of having a universal set of criteria that are applicable to most pile types with the risk that the same criteria may be inadequate for some particular pile types. Also, it may be difficult to meet objective (a) and (b) concurrently. A set of criteria that are technically sound for one pile type may not be so for another. For driven piles founding in soils, it will be reasonable to include the pile tip movement δ_{tip} as a component of the total settlement criterion. For rock socketed H-piles, the pile load is expected to be resisted predominantly by the shaft friction in soils and the rock socket. There will be hardly any load transferred to the pile tip and it will therefore be unreasonable to include δ_{tip} as a component of the total settlement criterion. If it is intended to adopt a single set of pile acceptance criteria applicable to a wide range of piles, one must lower his expectation in meeting objective (a).

Before exploring suitable simplifications for the current pile acceptance criteria, it is useful to summarize some of the viewpoints already discussed earlier.

a. It is not satisfactory nor technically sound to adopt a constant settlement limit for the total settlement criterion. As the total settlement tends to increase with pile length, a constant settlement limit will not be effective in controlling the performance of piles for different lengths.
b. The total acceptance criterion should take account of settlement due to pile shortening. It is sensible to incorporate the pile shortening δ_e as a component of the total settlement criteria. The calculation of δ_e based on $\alpha = 1$ as suggested by Davisson (1972) is considered to be a reasonable and practical recommendation as the observed value of α is often close to unity.
e. The expression of δ_{tip} in Davisson criterion is small and generally not sufficient to mobilize failure of soils at the pile tip. The end result is that the Davisson criterion is conservative and failure load determined by the criterion is usually not close to reaching the ultimate capacity of the pile.
c. The Brinch Hansen criterion is only a tool for predicting the ultimate capacity of piles. It is less conservative than the Davisson criterion in controlling the design failure load and pile performance in terms of settlement.
d. The residual settlement criterion of Eq.2 or Eq.4 previously or currently used by the BD, HD and ASD is not rational. Eq.4 is a relaxation only for piles with a poorer performance that exhibit a higher total settlement. Such a benefit cannot be enjoyed by well performing piles with a smaller total settlement because they often have a higher observed residual settlement caused by residual loads.
e. The residual settlement bears little direct relation to the settlement of pile under working condition which is more relevant in controlling building settlement.

There are already numerous total settlement criteria available in the literature as described by Fellenius (1980), Fraser & Ng (1990) and many others. The different pile acceptance criteria are developed based on experiences or techniques of curve fitting without a strong theoretical justification. One will doubt whether a technically sound criterion can actually be developed as pile behaviour is too complex to predict and affected by too many factors. There is no point to suggest yet another a set of entirely new pile acceptance criteria. At present, the total settlement criterion used in Hong Kong is either the Davisson criterion or the Brinch Hansen criterion. Foundation engineers in Hong Kong are familiar with both sets of criteria. One can further review the two sets of criteria to examine if possible simplification can be made.

The author is of the view that the Brinch Hansen criterion is a less preferable total settlement criterion from a practical point of view. The Brinch Hansen criterion demands the load-settlement curve to be well defined, including the curve beyond the design failure load often required for interpreting the actual failure load. In the current practice, the test pile will be loaded to the maximum test load in 4 stages according the loading test procedures specified by the BD, HD and ASD and in three stages according to CEDD. There will only be limited data points for defining the full range of load-settlement curve and this will not be sufficiently refined to allow a reliable determination of the ultimate pile capacity using the Brinch Hansen criterion.

In the CEDD pile acceptance criteria, the Brinch Hansen criterion is for assessing the failure load. A stringent limit on the settlement at working load has been specified as an additional criterion by the CEDD for controlling the pile performance. As a result, the determination of failure load using the Brinch Hansen criterion will become a somewhat redundant exercise as it is not the critical condition.

In comparison, the Davisson failure criterion is a considered to be more practical format for formulating the total settlement criterion because:

a. It is now widely accepted by BD, HD and ASD.
b. It is acceptable to a wide range of piles as $\alpha = 1$ is adopted for evaluating the pile shortening δ_e in the criterion.
c. It is relatively conservative mainly because the magnitude of δ_{tip} in the criterion is too small to cause ultimate failure of the pile. Because of this inherent conservatism, the settlement of a pile which passes the Davisson criterion is generally small. If this is the case, the Davisson criterion alone will be sufficient to be used as the single criterion for preventing failure of the pile and controlling its settlement.

As discussed earlier, the magnitude of δ_{tip} is still small, being 10.25mm, even for piles with lateral dimension up to 750mm for which a loading test will be required for proof-testing. Without compromising the conservatism of the Davisson criterion to any significant degree, it is proposed to simplify the Davisson criterion as follows for all piles no exceeding a dimension of 750mm.

$$\delta_{max} = \frac{P \times L}{A \times E} + 10 \qquad \text{(in mm)} \qquad (5)$$

With this simplification, it is no longer necessary to define the pile dimension *D* and one can avoid the confusion of different definitions of *D* used by different government departments.

Another proposal is to delete the residual settlement criterion for reasons already explained earlier and in line with the suggestions made over 30 years ago by Fraser & Ng (1990). With this, Eq.5 will become the whole and the only criterion for pile acceptance based on the author's proposal.

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APPENDIX

In this Appendix, a simplified approach is used to illustrate how residual settlement can occur after release of loading after a loading test based on the following simplifying assumptions (see Figure 3).

a. The pile head is at the ground surface.
b. The shaft resistance $\tau(z)$ varies linearly with depth z
c. The pile is sufficient long such that total shaft resistance itself is sufficient to resist the maximum test pile before reaching the pile toe.

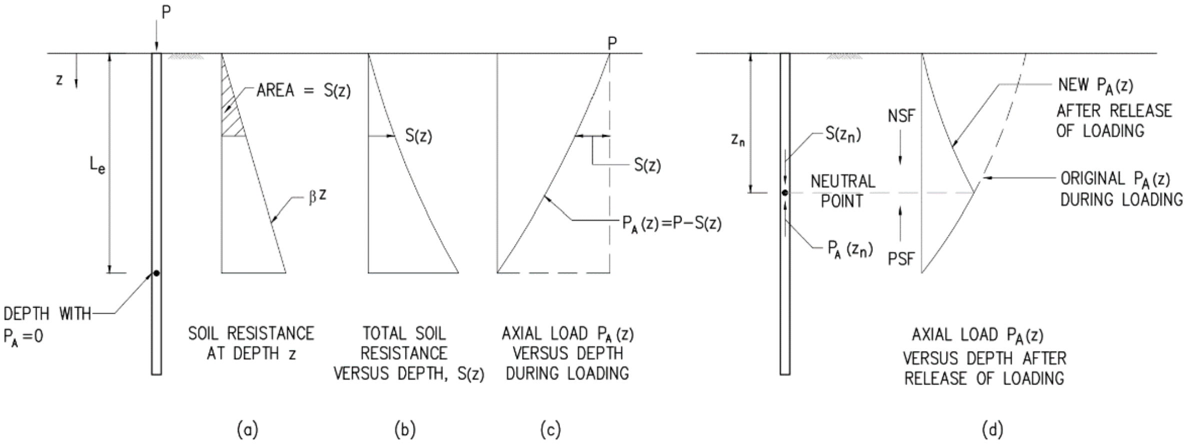

Figure 3: Force distribution along a pile during a loading test

Assumption (b) may be reasonable for a replacement pile installed in a uniform soil profile with the groundwater near the ground surface. Figure 3(a) to (c) show the distributions of shaft friction $\tau(z)$, total shaft resistance $S(z)$ and the axial load $P_A(z)$ at depth z below the pile head respectively according to the above assumptions. L_e is the pile length at which the total shaft resistance is sufficient to balance the applied load test P. The relationships between these quantities can be expressed as:

$$\tau(z) = \beta \times z \tag{6}$$

$$S(z) = \beta \times \frac{z^2}{2} \tag{7}$$

$$P_A(z) = P - S(z) \tag{8}$$

When $z = L_e$, $P_A = 0$ and this gives:

$$P = S(L_e) = \beta \times \frac{{L_e}^2}{2} \tag{9}$$

The total settlement due to pile shortening is given by:

$$\delta_{max-observed} = \int_0^{L_e} \frac{P_A(z)}{A\times E}\, \mathrm{d}z = \frac{1}{3} \times \beta \times \frac{{L_e}^3}{A\times E} \tag{10}$$

By solving Eq.9 and 10, we can obtain closed form solutions for β and L_e. When the test load is fully released, the upper portion of the pile will rebound causing reversal of shaft friction (i.e. NSF) to develop. The shaft resistance at the lower portion of pile remains unchanged because the rebound movement cannot reach such depths. There will be a neutral point at which the downdrag caused by the NSF above the neutral point will be equal to the total PSF which has originally developed below the neutral point at full test load, leading to new equilibrium of the pile after full release of test load. By assuming that the magnitude of shaft resistance will remain unchanged after stress reversal, the neutral point can be obtained by solving the following equation.

$$S(z_n) = P_A(z_n) \tag{11}$$

By substituting Eq.7 and 8 into Eq.11, one can obtain the solution for the depth of the neutral point z_n. Based on the solutions for β, L_e and z_n, the following closed-form solution can be obtained for predicting residual settlement $\delta_{r\text{-}predicted}$.

$$\delta_{r-predicted} = \int_0^{z_n} \frac{P_A(z)}{A \times E}\, \mathrm{d}z + \int_{z_n}^{L_e} \frac{P_A(z)}{A \times E}\, \mathrm{d}z = \delta_{max-observed} \times \left(1 - \frac{1}{\sqrt{2}}\right) \tag{12}$$

Using the relevant input parameters for Pile B, the effective length L_e is estimated to be above the rockhead level of pile, thus justifying the above assumption (c) in the analysis. The predicted residual settlement given by Eq.12 is 10.3mm for Pile B, which is close to the observed residual settlement.