Study of Creep Settlement of Driven H-piles in Loading Tests

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Abstract

In Hong Kong, the maximum test load is required to be maintained constant for 72 hours during loading tests of piles according to the loading test procedures in the Code of Practice for Foundations 2017. Such a long duration of maintained loading is uncommon in pile loading tests overseas. In the paper, the behaviour of driven H-piles under maintained loading will be studied using creep settlements measured during the 72 hours of maintained loading of piles from various sites in Hong Kong. The reason for such a long period of maintained loading is not discussed in the literature. The paper aims to address the more fundamental issues of (a) usefulness of maintained loading if any, (b) whether it is meaningful to conduct maintained loading at peak test load and (b) whether the period of maintained loading can be reduced the time needed for loading test.

Keywords: Driven H-piles, Maintained load tests, Creep settlement

1 Introduction

In Hong Kong, quality assurance of pile foundation is usually implemented by means of loading tests, except for bored piles with pile diameter exceeding 750mm. According to the Code of Practice for Foundations issued by the Buildings Department (BD) (BD, 2017), loading tests for pile foundations are to be carried out based on the following steps, where WL denotes the design allowable capacity of the pile.

1st loading cycle: $0 \rightarrow 0.5$ WL $\rightarrow$ WL $\rightarrow 0$

2nd loading cycle: $0 \rightarrow 0.5$ WL $\rightarrow$ WL $\rightarrow 1.5$ WL $\rightarrow$ 2WL (72 hours) $\rightarrow 0$

For each load increment, the pile settlement rate has to attain a certain threshold value before the next load increment and likewise for a load decrement. In the first loading cycle, the maximum test load is equal to WL. In the second loading cycle, the maximum test load is twice the design allowable capacity and will be maintained constant for 72 hours before release of loading at the end of loading test. Because of the requirement of a long period of maintained loading, loading tests for private projects in Hong Kong are commonly started on Monday, Tuesday or Friday to allow representatives from the BD to witness the application of loading to peak test load and final release of loading on a working day on weekdays. The Architectural Services Department (ArchSD) also adopts the same procedure as the BD for pile loading test (ArchSD, 2020).

According to the Code of Practice for Foundations (BD, 2017), a pile will pass a compression loading test if the measured settlements at pile head do not exceed the following two limits.

Total settlement (in mm): $2WL/AE + D/120 + 4$

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Residual settlement (in mm): D/120 + 4 or 25% of maximum pile head settlement during the test, whichever is larger

where *A*, *E* and *D* are the cross-sectional area of the pile, Young's modulus of the pile material and the least dimension of the pile, respectively. The ArchSD adopts the same pile acceptance criteria except that *D* is taken as the least dimension of a driven H-pile, the outer diameter of steel casing of a mini-pile or the diagonal of rectangle enclosing the H-section of a rock-socketed steel H-pile. The maximum settlement criterion for the total settlement is often called the Davisson's criterion because it is based on an old publication by Davisson (1967).

The Civil Engineering Development Department (CEDD) adopts a loading test procedure different from that of the BD and ArchSD. For preliminary piles, the maximum test load is *P* = 2WL. For working piles, the maximum test load should not be less than *P* = 1.8 WL. As described in CEDD (2020), the test loads are applied in three increments to reach the maximum test load *P* as follows:

$$0 \rightarrow 0.25\,P \text{ (24 hours)} \rightarrow 0 \rightarrow 0.5\,P \text{ (24 hours)} \rightarrow 0 \rightarrow P \text{ (24 hours)} \rightarrow 0$$

For each stage of loading, the maintained loading will last for at least 24 hours until the settlement rate has reduced to less than 0.1mm/hour. The total duration of maintained loading will also be 72 hours, but divided into three periods of 24 hours. The CEDD adopts the Brinch Hansen's criteria (CEDD, 2020) in lieu of the Davisson's criterion for pile loading test, and there is no settlement criterion for the residual settlement.

This paper aims to discuss the following basic questions related to pile loading tests:

a. Is maintained loading necessary?
b. At which stage should the maintained loading be applied?
c. What is the suitable duration for maintained loading?

In this paper, discussion will only be focused on driven steel H-piles under maintained loading under compression in loading tests.

2 Function of Maintained Loading

When a constant load *P* is applied to a stable pile, the pile settlement δ will not stop immediately after loading application, but gradually reduces with time. For practical purpose, some criteria need to be specified for defining the pile settlement corresponding to the applied load *P* at equilibrium condition. These criteria are usually in the form of a minimum holding time T_h and/or a threshold settlement rate *r*.

For a load increment, the BD and ArchSD specify a holding time of 10 minutes and a threshold settlement rate of 0.05mm in 10 minutes, whichever takes a longer time to attain (BD, 2017; ArchSD, 2020). For a load decrement, the holding time is increased to 15 minutes and the threshold recovery rate is 0.1mm/hour. The CEDD specifies a threshold settlement rate of 0.1mm in 20 minutes for load increment only (CEDD, 2020).

In Singapore, a threshold settlement rate of 0.25mm/hour for loading increment is recommended in their Code of Practice for Foundations CP4:2003 (2012) (Singapore Standards Council, 2012). A similar

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threshold settlement rate seems to be also used in Malaysia (G&P, 2005; Foundtest, 2021). Figure 1 shows the schematic diagram of pile settlement under a constant applied load.

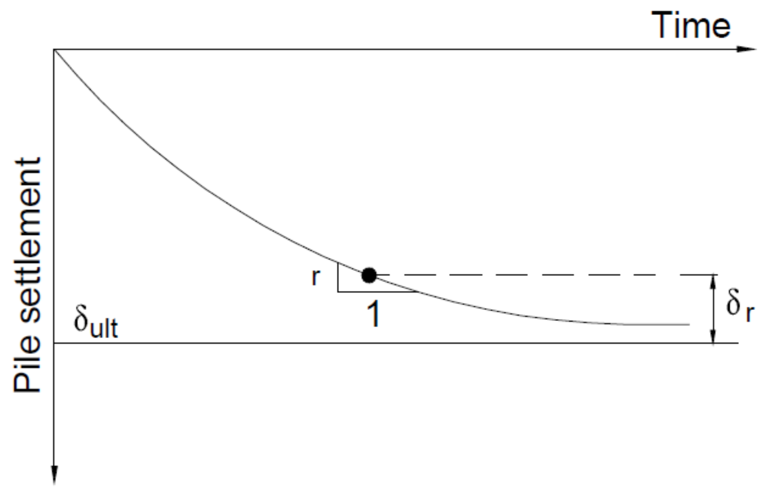

Figure 1: Pile settlement under constant loading

For a pile deriving its resistance mainly from sandy soils, dissipation of pore-water pressures is expected to occur quickly and the pile settlement during constant applied load may be attributed to creep movement of soils. For piles embedded in softer soils, such as continuous flight auger piles which have now become uncommon in Hong Kong, the pile settlement under constant loading may be a combination of consolidation and creep settlement.

In Hong Kong, driven piles are usually founded in dense sandy soils. Therefore, pile settlement under constant applied loading is expected to be dominated by creep settlement. Based on the experiences gained from jacked piles (Li *et al*., 2003), creep settlement tends to approach an asymptotic value δ_{ult} as indicated in Figure 1. Similar behaviour is expected to also occur for driven piles in sands. If the settlement has reached a small enough threshold settlement rate *r*, it is expected that remaining or residual settlement δ_r as indicated in Figure 1 will be small.

According the loading test procedures specified by BD and ArchSD, maintained loading has to be applied for 72 hours at the test load of 2WL. The practice of maintained loading for loading tests in Hong Kong for private development projects dates back to at least 60 years ago (Philcox, 1962). Maintained loading are not uncommon in loading tests in other parts of the world, but the holding time of applied load usually ranges from a few hours to one day. Hong Kong is perhaps the only example in which the duration of maintained loading is as much as 72 hours.

The question then arises as to the purpose of maintained loading. What is to be gained by spending the time on such a practice? If there is a good reason for such a practice, one will expect that the rationale for it should have been well discussed in the literature. To date, the authors are unaware of any publication that describes the advantage of maintained loading. It was neither discussed in Philcox (1962), nor even required by Davisson (1970) as part of his proposed pile acceptance criterion for total settlement. Perhaps, Fellenius & Nguyen (2019) have rightly remarked that "for tests employing unequal load increments, unequal load-holding, and unloading-reloading events, the attitude seems to be: *we did it last time, so why not keep on doing it?*" and that "no useful information is obtained from prolonging the holding time for the maximum load".

In our opinion, there appears to be little sound technical justification for imposing the requirement of maintaining the applied load for a long period of time in a loading test. If there is a concern that ultimate creep settlement of a pile is excessive, the best strategy is to use suitable threshold settlement rate *r* as alternative to prolonged maintained loading for assessing the ultimate creep settlement of pile. If the specified magnitude of *r* is sufficiently small, the total pile settlement that will occur upon reaching threshold the settlement rate will be for all practical purposes a close estimate of the ultimate creep settlement. It is much more efficient and rational than performing a prolonged maintained loading of 72 hours for assessing the residual creep.

The use of a threshold settlement rate has proven to be a practical tool for controlling the creep settlement of jacked piles (Lam, 2007) and the same is expected to be equally feasible for driven piles.

3 When to Conduct Maintained Loading

As discussed in the preceding section, there is no sound justification for the requirement of maintained loading. If such a requirement has to be imposed by the regulatory authority, the question then is at what load level should the maintained loading be preferably applied?

Figure 2(a) shows a schematic load-settlement response of a driven pile under normal condition. When a driven pile is installed, the pile will be subjected to virgin loading from zero to 2WL or perhaps higher due to the transient driving force of the hammer. The load path is described by the line O-A-B. After installation, the applied loading will drop to zero, represented by the load path B-C. When the structure supported by the pile foundation is gradually built, the pile will undergo reloading due to the dead load of the structure, causing the load path to change from point C to D upon completion of the building as depicted in Figure 2(a). During the life span of the building, the pile load will fluctuate between point D and point E in response to fluctuations in loading due to temporal variations of superimposed dead loads, live loads and etc., but the maximum load is expected to be within the design working load of the pile.

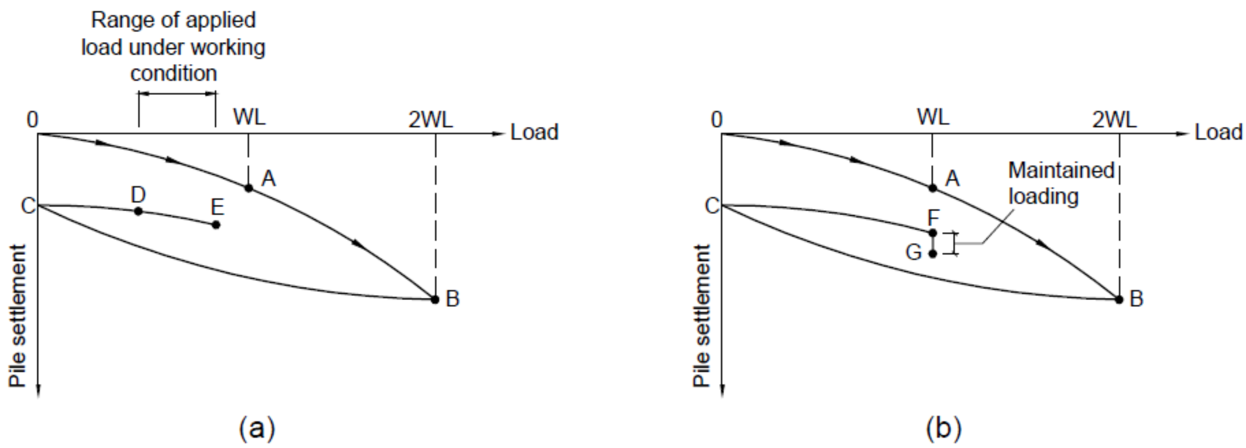

Figure 2: Load-settlement of pile (a) anticipated response under working condition (b) preferred load cycle for maintained loading

The loadings applied to the pile during installation from point O, A and B are transient loading. Maintained loading will not occur in reality in this load path for a working pile. Only when the building is being constructed or has been completed under a load path from point C to E in Figure 2(a) will slow or maintained load be applied to the pile foundation. More importantly, the maintained load experienced by the piles under working condition will not exceed the design working load of the pile, WL. Because of this observation, it is theoretically not justifiable to impose a maintained loading at 2WL in a loading test.

If a maintained loading has to be imposed on a loading test to observe the behavior of the test pile under long-term load at working condition, it is more logical to conduct such a test at WL represented by point F to G in Figure 2(b). Based on this suggestion, the BD's loading test procedures can be modified as:

1st loading cycle: 0 $\rightarrow$ 0.5 WL $\rightarrow$ WL (maintained loading) $\rightarrow$ 0

2nd loading cycle: 0 $\rightarrow$ 0.5 WL $\rightarrow$ WL $\rightarrow$ 1.5 WL $\rightarrow$ 2WL $\rightarrow$ 0

Similarly, the CEDD's loading test procedure can be modified as:

0 $\rightarrow$ 0.25 P $\rightarrow$ 0 $\rightarrow$ 0.5 P (maintained loading) $\rightarrow$ 0 $\rightarrow$ P $\rightarrow$ 0

4 What Is Suitable Duration of Maintained Loading

If the requirement for maintained loading has to be imposed in a loading test, what is a suitable holding time for the maintained loading? To address this question, data on pile settlement obtained during the 72 hours of maintained loading in loading tests conducted according to the BD's loading test procedures is analyzed. Such data will be useful for making a suitable recommendation for the duration of load-holding.

In Hong Kong, it has now become a common practice to measure the pile settlement using both dial gauges and LVDTs. However, formal records of pile settlement are still based on dial gauge readings whereas the LVDT readings are often treated as backup data. The dial gauge readings are usually taken at less frequent intervals, but the LVDT readings are commonly taken much more frequently and automatically by data loggers.

Although the technology of servo-control for regulating the applied load is well established, it is not a mandatory requirement and not often used in pile loading tests. Manual control of applied load is usually preferred by contractors, whereby the jacking pressure of the hydraulic jacks is adjusted manually before the dial gauge readings are taken. If the hydraulic pressure of the loading jack is not held constant by servo-control and not adjusted frequently, the hydraulic pressure may drop leading to drop in applied load and reduction in creep settlement of the pile.

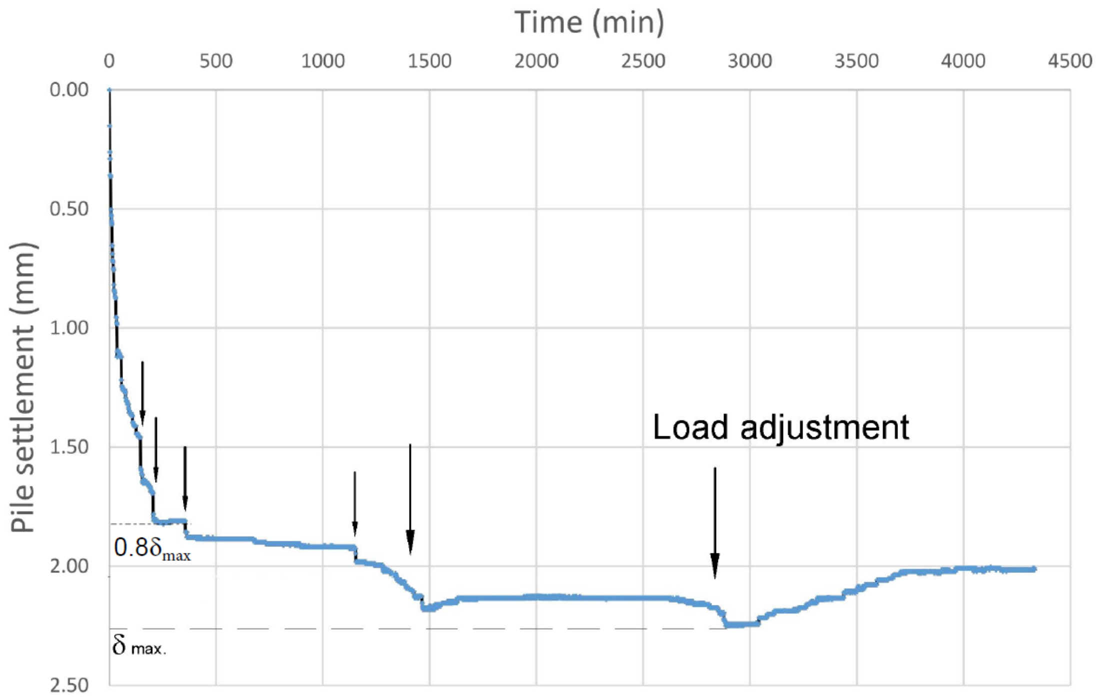

Figure 3: Setlement curve of a driven pile during maintained loading

Figure 3 shows the settlement curve for a Grade S460 305x305x223 kg/m UBP subjected to maintained loading of 7100 kN for 72 hours. The settlement readings were recorded by LVDTs every minute while the applied load adjusted manually. The following general observations can be made.

- The settlement increases rapidly at the early stage of the maintained loading, a large percentage of the total pile settlement measured during the 72-hour period has occurred within the first few hours of maintained loading;
- The rate of settlement reduces with time and tend to approach an asymptotic value.
- There are perturbations in the load-settlement curve.

If the constant applied load is achieved by manual adjustment, small adjustments are close time intervals will be necessary to maintain the load at a reasonably uniform level. This will be a very demanding task for the technicians conducting the loading test. More often, larger load adjustments are carried out at long time intervals to reduce the effort of load adjustment, resulting in larger perturbations in the load settlement curve as illustrated by Figure 3. If the time elapsed between load adjustment is long, significant recovery of pile movement may be observed during “maintained loading” causing the pile to rebound as exemplified by the data in Figure 3. Fellenius & Nguyen (2019) have reported similar observations from case histories of pile loading tests in which the applied loading for maintained loading was adjusted manually.

The above observations are quite typical of the results of maintained loading test for driven piles in Hong Kong. Figure 4 compiles settlement curves of some other driven piles showing a range of typical settlement curves under 72 hours of maintained loading, with some showing distinct perturbations similar to that of Figure 3.

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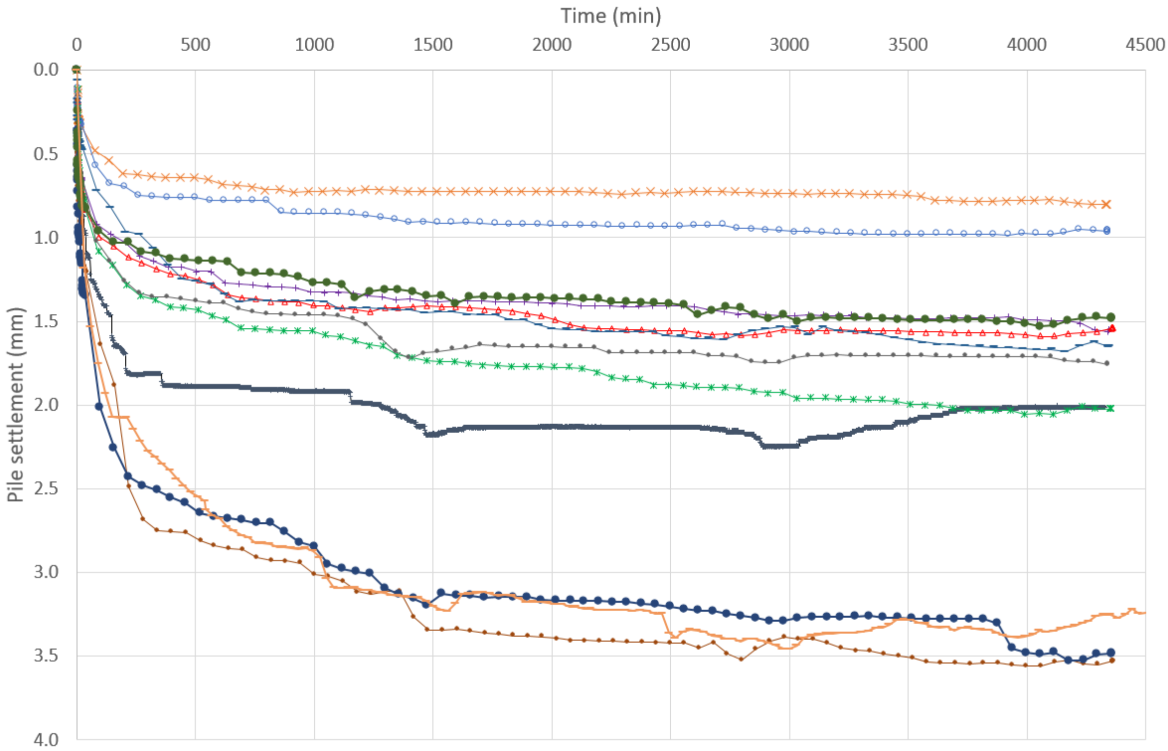

Figure 4: Typical settlement curves of driven piles from various sites in Hong Kong during maintained loading

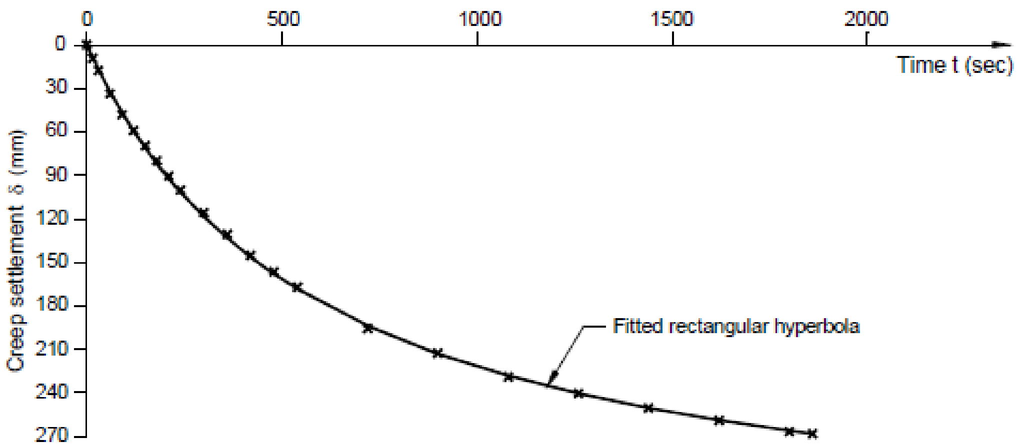

Figure 5: Setlement curve of a jacked pile under maintained load (Lam, 2007)

If servo-control is employed for regulating the applied load, it is expected that a smoother settlement curve will be obtained for maintained loading. Figure 5 shows the load-settlement curve of a jacked pile under constant loading reported by Lam (2007). The applied load had been controlled and maintained at a reasonable constant level by servo-control. As a result, a much smoother settlement curve could be obtained for the creep settlement of the jacked pile and the settlement curve can be well fitted by a rectangular hyperbola. A similar settlement curve is expected for driven piles if servo control is used to maintain the applied load to a constant level throughout the load holding period.

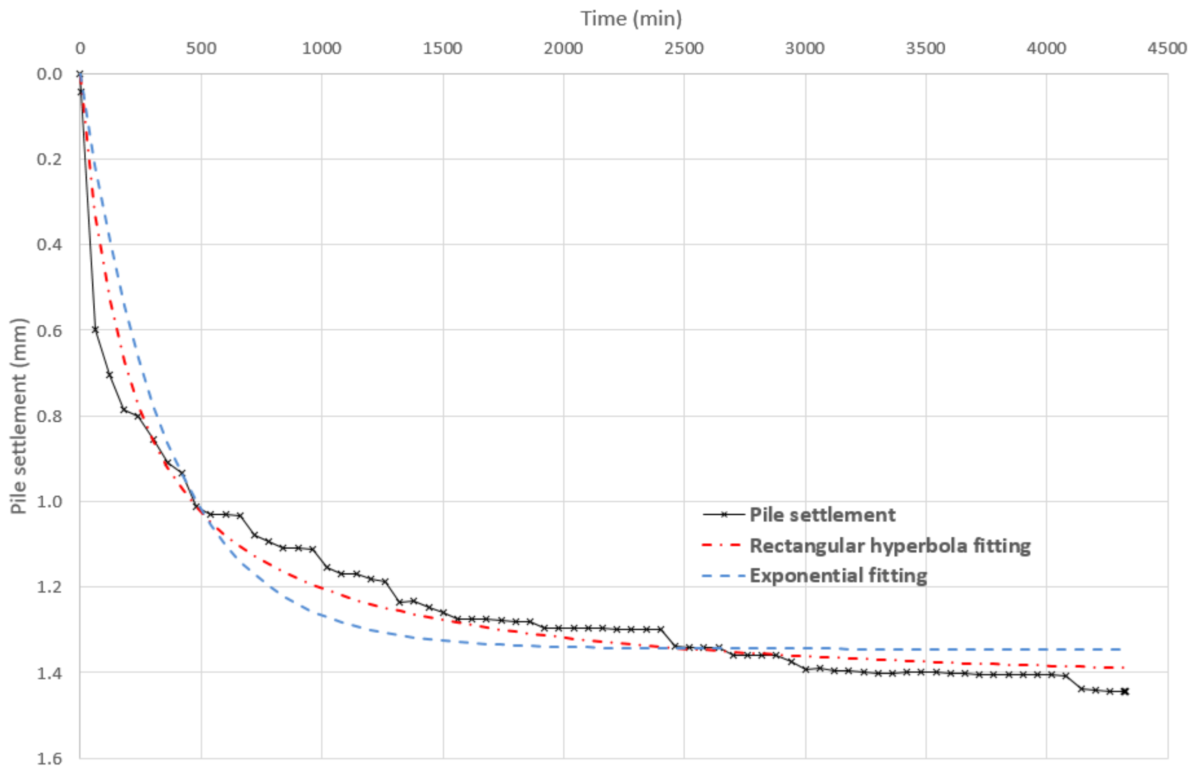

Figure 6: Curve fitting of a setlement curve of a driven pile under maintained load

Figure 6 shows an example of a settlement curve of driven H-pile which does not exhibit large perturbations during the 72 hours of maintained loading at 2WL. It manifests that creep settlement curves can to a certain extent be reasonably fitted by a rectangular hyperbola or an exponential curve of the following form:

rectangular hyperbola: $\delta = a\,t\,/(b + t)$

exponential curve: $\delta = a\,(\,1 - e^{-b\,t}\,)$

where *a* and *b* are parameters to be fitted. However, the goodness of fit can be significantly affected by perturbations in the pile settlement curve caused by load adjustment.

To assess whether there is room for reducing the duration of maintained loading, the settlement curves during the 72 hour of loading at 2WL for 20 loading tests conducted on driven piles at different sites in Hong Kong using the BD's loading test procedures are studied. Referring to Figure 3, the maximum settlement δ_{max} recorded during the 72 hours of maintained loading is identified. The settlement corresponding to 80% of δ_{max}, denoted by δ_{80}, is then read directly from the settlement curve. The following table summarizes the results of δ_{80} for settlement curves presented in Figure 4.

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Table 1. Summary of δ_{80} for maintained loading test

Pile no.	δ_{80} (mm)	Time to reach δ_{80} (hr.)	Pile no.	δ_{80} (mm)	Time to reach δ_{80} (hr.)
1	1.3	10	11	1.2	15.1
2	1.3	9.1	12	2.9	17.1
3	1.6	20.8	13	0.5	3.0
4	1.3	10.4	14	1.4	12.0
5	1.7	4.7	15	0.7	23.6
6	1.3	28.4	16	1.8	3.5
7	1.4	10.5	17	1.6	20.8
8	2.8	10.2	18	0.9	23.3
9	1.8	7.5	19	0.8	45.3
10	2.8	15.6	20	1.2	20.2
The above piles are Grade S450J0 305x305x 223 kg/m UBP with design capacity ranging from 2950 kN to 3670 kN founded in soil profile consisting of fill, alluvium overlying completely decomposed granite.					

The following observations can be made from the results of Table 1.

a. The settlement that occurred during maintained loading is small, mostly within 2mm for the data presented in Table 1.
b. 80% of creep settlement that occurred during the 72 hours of maintained loading will generally within the first 24 hours.

The results of creep settlement presented in Table 1 were collected during maintained loading at 2WL. As explained earlier, the magnitude of maintained loading acting on the piles under working condition will not exceed WL.

It is well established in soil mechanics that preloading will contribute to a significant reduction in creep settlement of soils and an increase in soil stiffness. This is the guiding principle used for installation of jacked piles (Lam, 2007). When jacked piles are installed, they are preloaded to a higher load level than 2WL so that the creep settlement will be sufficiently small to pass the loading test conducted at 2WL both in terms of total and residual settlement criteria.

Similarly, driven piles will be preloaded by driving force of the hammer to a load level equal to or higher than 2WL during installation. It is therefore expected that the creep settlement of piles at a lower load level of WL under the working condition will be much smaller and occur much faster than that occurring under maximum test load at 2WL. Figure 7 shows the settlement curves of a driven pile measured in the first cycle of load-holding at WL and in the second load-holding cycle at 2WL in a pile loading test conducted according to the BD's procedures.

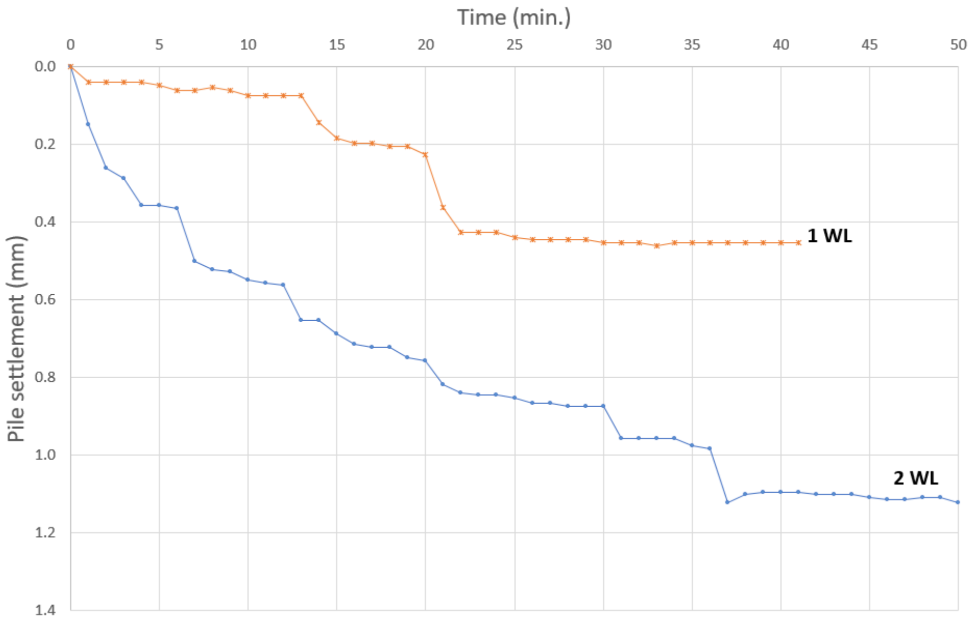

Figure 7: Setlement curves of a driven pile under constant loading of WL and 2WL

It is noticeable from Figure 7 that the creep settlement of the pile at WL is smaller and approaches the asymptotic value much more quickly than that at 2WL, in a matter of few tens of minutes.

5 Conclusions

A review of the practice of imposing maintained loading during a load test is presented. The following suggestions are made.

a. Servo-control is recommended for maintained loading to enable the applied loading to be held constant. This will reduce the occurrence of perturbations in the load settlement curve.

b. There is no good reason for a requirement of maintained loading. If there is a concern that the residual creep settlement may be significant, a more rational and efficient approach of loading test is to specify a suitable threshold settlement rate instead of spending days on performing maintained loading in a loading test.

c. It is also not logical to conduct the maintained loading test at maximum test load as required in the BD's or CEDD's loading test procedures. The installed piles will only be subjected to slow increase in loading during construction and service life of the structure and the applied loading under working condition will not exceed WL. If maintained loading has to be conducted as a statutory requirement, it is more logical to conduct maintained loading at the load level of WL instead of the maximum test load. Based on the results of Table 1, the creep settlement at 2WL is typically small. It is expected that the creep settlement under maintained loading at WL is insignificant.

d. Based on the settlement data of driven piles from maintained loading conducted at 2WL, it is found that creep settlement of pile will mostly be completed in one day. Further creep settlement occurring between 24 hours and 72 hours is relatively small, and typically less than 0.5mm. If maintained loading has to be conducted as a statutory requirement, there is room for reducing the holding time to 24 hours or less and/or specifying a suitable threshold settlement rate for terminating the maintained loading to reduce the total time needed for loading test without any significant effect on results of loading test as compared with the current practice. If the maintained loading can be conducted at WL, creep settlement is expected to smaller and occur much more quickly and perhaps a holding time of a few hours will be more than sufficient.

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