The 5th Cross-strait Conference on Structural and Geotechnical Engineering (SGE-5)
Hong Kong, China, 13-15 July 2011

INSTALLATION LOAD AND WORKING CAPACITY OF JACKED PILES: SOME EXPERIENCES IN CHINA

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ABSTRACT

The working capacity of jacked piles may be self-proved by the load experienced during installation, since the press-in penetration and the static loading test have similar physical background. The ratio of pile's ultimate capacity to the final jacking load, defined as the pressure ratio in this study, is an interesting but tricking issue in jack piling design and construction. Focus is paid on how the pressure ratio varies with pile's slenderness ratio and the condition of surrounding and end-bearing soils. With a primary concern on the concrete piles widely used in China, several empirical correlations used in practice are summarized and examined. A new database, with test piles collected from different parts of China, is then presented in an attempt to seek for an effective way to consider the effect of soil condition. A simple sorting method in terms of fine and coarse soils has the potential to properly consider the different behaviors arising from the pile-equalization stage.

KEYWORDS

Displacement piles, jacking load, ultimate capacity, slenderness ratio, empirical correlations.

INTRODUCTION

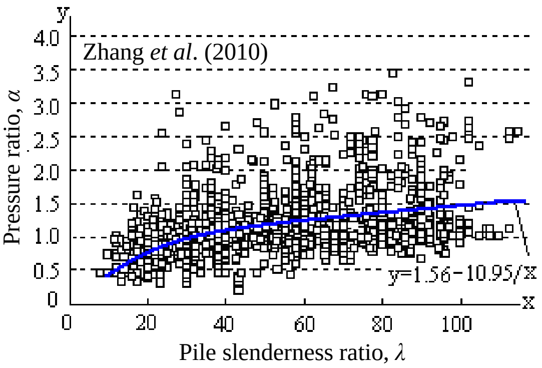
Installation of displacement piles traditionally involves a procedure of dynamic driving; alternatively, the piles can be statically pressed into the ground. Driven piles have been encountering serious problems of noise and vibration; and nowadays they are only used in suburb and offshore area. Press-in construction, also known as jack piling, eliminates the adverse effect of pile installation on the surrounding environment. Moreover, jacked piles have advantages that the risk of structural damage during installation is reduced and the achieved capacity is larger than that of driven piles (Yang *et al*. 2006a). Jack piling is relatively novel in Australia, Europe and North America and also unfamiliar to the piling industry in Hong Kong (GEO 2006). The popularity of jacked piles is received within the recent two decades in Mainland China, largely due to that: (1) the application of hydraulic jacking rigs up to 1000 ton capable of pushing piles into strong soils and; (2) the industrialization of producing prestressed concrete pipe piles with high structural strength. While the jacked piles used in Mainland are largely concrete-type, their limited use in Hong Kong is concentrated to steel H-pile (Lam 2007).

Termination criteria describe the conditions that control the accomplishment of jacking construction. Besides the requirement of least pile length, a typical set of termination criteria may specify: (1) the final jacking load which should be stably held for some time; (2) the number of rejacking cycles and; (3) the duration of each jacking cycle. For instance, the Chinese pile design code (JGJ94 2008) gives a general guideline that: (1) the final jacking load shall be determined on installing trial piles; (2) the rejacking cycles shall be 2~5 times, less for shorter piles and; (3) the final jacking load shall be repeated and maintained for 5~10 seconds per cycle. Among these factors the final jacking load is crucial for proper execution of jack piling. Practical participants will feel it convenient to predict a pile's capacity simply according to the jacking log or suggest suitable installation proposal to satisfy the design capacity. Some modern jacking machines have been equipped with device that is able to measure real-time jacking resistance and predict pile capacity (Peng and Lu 1999).

This paper presents current understandings of the relation between the final jacking load and the ultimate capacity of jacked piles. Test data are collected and interpreted from many case histories in China to investigate their relationship and, therefore, to allow for rational design and construction of jacked piles.

PHENOMENON AND MECHANISM

The physical base of jacking penetration is very similar to that of static loading. Both the final jacking load (P_j) and the ultimate capacity in the static load test (Q_u) can be deemed as "failure load" with regard to the failure of the pile-soil system. It may be noticed that the apparent difference between these two procedures is the rate of penetration which is much greater during installation. Also keeping in mind that a fast loading rate generally results in greater failure load than a slow rate does (Jardine and Bond 1989), the ultimate capacity would fall below the magnitude of the final jacking load. This is, however, inconsistent with many field observations. Zhang *et al*. (2010) compile a database containing nearly 2000 jacked open-ended concrete pipe piles in various soils in Zhejiang, as shown in Figure 1. The relationship between P_j and Q_u seems rather complicated; and the underlying mechanism needs to be explored further. For this purpose, it may be helpful to compare the load transfer characteristic of displacement pile subjected to the same level of jacking load and static load. Figure 2 is an example of a jacked steel H-pile tested at a reclamation site in Hong Kong (Yang *et al*. 2006b).



Notations:
α, pressure ratio equal to the ratio of ultimate pile capacity to final jacking load
λ, pile slenderness ratio equal to the ratio of pile length to pile outer diameter

Figure 1 Variation in the ratio of ultimate pile capacity to final jacking load

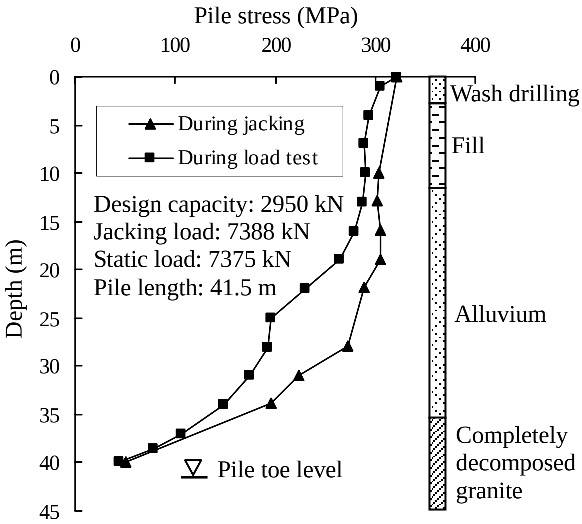


Figure 2 Load transfer of a jacked pile during installation and static load test

Figure 2 shows that, given the similar pile-head load level, the two curves differ primarily in the mobilization of local shaft resistance in the lower portion. The jacking load is resisted by the soil at deep depth. The shaft resistance at shallow depth, say some level within 20 m below the ground, is insignificant. This can be attributed to the release of contact between the penetrating pile shaft and the surrounding soil where even broad void has been visually observed during installation (e.g. Lam 2007). The jacking shaft resistance developed in deep soil is larger than that under static loading while the base resistances at the two phases are comparable. "Failure" occurs at any depth in the pile-soil system during installation. Nevertheless, the definition of "ultimate state" under static loading is much complex and; both the shaft resistance at deep depth and the base resistance are very likely to be far below the ultimate strength. Actually the test pile has been statically loaded to maximum 9735 kN which exceeds its structural capacity; geotechnical failure has not been achieved yet according to the load-settlement performance (Yang *et al*. 2006b).

It can be concluded that under the static loading level equivalent to the final jacking load, the shaft and base resistances in deep soil have the potential to increase. For this pile, of course, the ultimate geotechnical capacity is expected to be much greater than the final jacking load. Such increase may result from the mechanism in relation to the pile-soil equalization after installation. During the equalization period, the set-up effect may be associated with a number of factors such as remolding, reconsolidation and long-term aging (Komurka *et al*. 2003). Soil property is the major concern on determining which factor predominates in a specified period. It is therefore important to examine the relationship between P_j and Q_u with primary regard to soil condition.

EMPIRICAL CORRELATIONS

Liu (2005) presents a statistical analysis on 266 concrete tubular and square piles jacked in various soils. The pressure ratio, defined as the ratio of ultimate pile capacity to final jacking load, is examined in a category of end-bearing soils including clayey soil, residual soil, sandy soil, gravel and completely weathered rock. The mean pressure ratio is found to be greater than unity for most cases and; the softer the end-bearing soil is, the greater the mean pressure ratio is. However, the scattering of data disables that analysis to establish convincing empirical correlations. It is noted that the pressure ratio, α is generally correlated to the pile slenderness ratio, λ

by hyperbola-type functions (Figure 1). That is

$$\alpha = A - \frac{B}{\lambda} \quad (1)$$

where $\alpha = Q_u/P_j$; the parameters A represents the maximum pressure ratio that long piles tend to be; the parameter B reflects the curvature of the function.

Table 1 summarizes some existing proposals in accordance with Eq. 1 for concrete square and tubular piles in Mainland. They are normally regional; the values of *A* and *B* rely on the local soil conditions. The first proposal is further revised to correlate the pressure ratio with pile length only, and its simplified form has been included in a regional code for jack piling in Guangdong (Lin and Wang 2004). The statistical analysis of Zhang *et al*. (2010) makes a step forward in sorting data by the condition of embedded soils. However, difficulty arises in identifying the accurate soil description for such a large database, especially for the surrounding soils which are usually layered. Despite the general trend tells that piles founded on softer soil have greater values of *A* and *B*, the two categories with founding soils of silt and sand are shown to be in a reverse manner. Also note that a large portion of the piles have not been loaded to failure, caution should be drawn on the uncertainty of extrapolating ultimate capacity based on the grey theory.

Table 1 Values of *A* and *B* for precast concrete piles in various soils in Mainland China

Reference	*Region*	*Pile geometry*	*Surrounding soils*	*End-bearing soils*	*A*	*B*
Lin and Wang (2004)[1]	Pearl River Delta	Square and tubular, mostly 10~25 m long	Fill, sludge, clay and sand	Various soils and rocks	1.45	14
Zhang (2004)[2]	Shunde	Not applicable	Not applicable	Not applicable	1.25	12
Deng (2006)[3]	Nanjing	Tubular, 11~33 m long	Fill, clay and silt	Clay and sand	1.12	9.67
Wang *et al*. (2008)	Henan	Tubular, 15~20 m long	Not applicable	Silty sand	1.1~1.4	10*A*
				Silty clay	1.8~2.2	10*A*
Sun *et al*. (2009)[4]	Zhengzhou	Tubular, 9~25 m long	Not applicable	Sand	1.15	14.63
Zhang *et al*. (2010)[5]	Zhejiang	Tubular, mostly 10~40 m long	Clay	Clay	2.12	18.62
			Clay	Silt	1.78	21.26
			Clay	Sand	1.82	18.53
			Clay	Gravel	1.26	9.85
			Clay	Rock	1.2	5.32
			General, soil condition not considered		1.56	10.95

Note:
1. This proposal does not classify soil conditions; values of *A* and *B* are inferred from those originally for 95% confidence line; 101 piles are involved in statistics.
2. Information on pile and soil is not provided in the reference; 26 piles are involved in statistics.
3. This proposal does not classify soil conditions; ultimate pile capacity is extrapolated from non-destructive load test results; 32 piles are involved in statistics.
4. Information on surrounding soils is not provided in the reference; 24 piles are involved in statistics.
5. This proposal contains 15 sub-proposals corresponding to different soil categories; typically five of them are presented herein; ultimate pile capacity is interpreted based on grey theory in case some piles are not loaded to failure; nearly 2000 piles are involved in statistics.

NEW DATABASE

As mentioned early, the pressure ratio is associated with a number of factors in the equalization period. The property of soil may decide which factor is crucial in the period from installation to static loading. The grain size of soil is very important in controlling the behavior of remolding and consolidation. Soils can be generally classified into fine soils including clay and silt, and coarse soils including sand and gravel (Craig 1997). Also note that most foundation piles are jacked through soft soils and founded on competent soils, what is illustrated in Figure 3 may represent the prevailing soil conditions encountered in piling practice. Because of the capability of static press-in, currently, jacked piles are seldom installed in very stiff and dense soils or strong rocks. The soils surrounding a jacked pile are normally fine soils, sometimes with alternating thin layer of coarse soils. The end-bearing soils can be fine or coarse soils with adequate strength. Therefore, in an effort to take into account the influence of soil condition on the pressure ratio, one may focus on two situations: (1) piles surrounded and founded in fine soils and; (2) piles surrounded by fine soils and founded on coarse soils.

In this study, a new database comprising 95 jacked concrete tubular and square piles in Mainland China is established to investigate the variation in pressure ratio under the two categories of soil conditions. Information on the involved piles is summarized in Table 2. The test piles are mainly from the coastal provinces in China, covering a wide range of lengths from 5 m to 60 m. Their pressure ratios varying with the pile slenderness ratio are plotted in Figure 4, where several relevant correlations suggested by Zhang *et al*. (2010) are compared.

Table 2 Information on the jacked concrete piles involved in the new database

Reference	*Pile shape*	*Pile length (m)*	*Number of piles*	*Main surrounding soil*	*End-bearing soil*	*Category/Symbol*
Han (1996)	Square	23.8	2	Clay	Clay	FF/△
Lin and Lin (2001)	Tubular	13.5	1	Clay	Sand	FC/•
Huang (2002)	Tubular	38~48	7	Clay	Clay	FF/△
	Tubular	22~40	5	Clay	Gravel	FC/•
Yang and Pu (2002)	Square	5~8	6	Clay	Clay	FF/△
	Square	13~15	6	Clay	Silt	FF/△
Zhang (2004)	Square	21~26	3	Silt	Silt	FF/△
	Square	24~50	12	Clay	Clay	FF/△
	Square	8.2	1	Clay	Sand	FC/•
	Square	60	1	Clay	Gravel	FC/•
Zhao *et al*. (2005)	Tubular	12~16	6	Clay	Clay	FF/△
	Tubular	17~19	6	Clay	Sand	FC/•
	Tubular	6~7	3	Clay	Cobble	FC/•
Deng (2006)	Tubular	18~24	4	Clay	Clay	FF/△
	Tubular	16~33	19	Clay, silt interlay	Sand	FC/•
Wang *et al*. (2008)	Tubular	15~17	3	Clay	Clay	FF/△
	Tubular	8~20	8	Clay	Sand	FC/•
Liu *et al*. (2011)	Tubular	35, 39	2	Clay	Clay	FF/△

Note: The categories of FF and FC denote piles surrounded mainly by fine soils but founded on fine soils and coarse soils, respectively. The symbols are consistent with what are used in Figure 4.

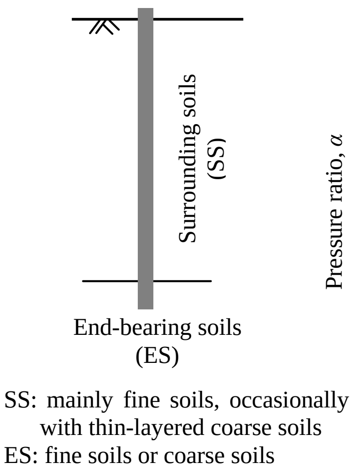


Figure 3 Common soil conditions for jacked piles

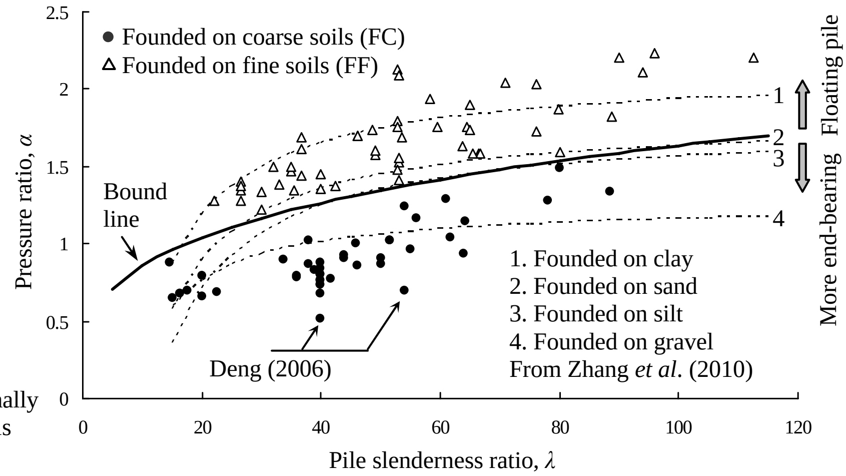


Figure 4 Relationship between pressure ratio and slenderness ratio for jacked concrete piles in fine and coarse soils

Figure 4 shows that most of the data in the FF category fall below the prediction of Zhang *et al*. (2010) for piles in clay (curve 1). The correlation for piles founded on sand (curve 2) apparently overestimates the data in the FC category which may be better fitted by the one for piles founded on gravel (curve 4). Overall, the grain size of soil has inverse effect on the pressure ratio. Note that the two lowest pressure-ratio data in Figure 4 come from Deng (2006) where the surrounding soils are alternating silty clay and sandy silt. Due to the scattering of data, the new database is immature to develop reliable regression correlations. The merit may lie in that the two categories of data can be explicitly separated by a bound line. Implications may be drawn that: (1) soil conditions have strong effect on the pressure ratio and; (2) it is feasible to classify the soil conditions roughly into the FF and FC categories. The bound line shown in Figure 4 can be expressed by

$$\alpha = 0.45\lambda^{0.28} \tag{2}$$

which is an exponential function rather than a hyperbola. Mathematically, Eq. 2 has advantage over Eq. 1 in well simulating the variation in pressure ratio at small slenderness ratio. Eq. 2 defines the lower and upper limits of pressure ratio for piles belonging to the FF and FC categories, respectively. Particularly for piles jacked into fine soils, in the light of reliability-based design, the bound line may be used to estimate pile's ultimate capacity according to the final jacking load. What should be pointed out finally is that, due to the increase in the capacity of jacking rigs, more and more piles are able to be jacked into entirely granular soils. Thus, a new category of soil condition (CC) needs to be developed in the future.

CONCLUSIONS

This paper investigates the capacity of jacked piles in relation to their experienced load during installation. The so-called pressure ratio, probably less or more than unity, depends on the slenderness ratio of pile and the soil condition which plays an important role in the equalization period. The hyperbolic relationships between the pressure ratio and the slenderness ratio are extensively examined for jacked concrete piles in China. With respect of the importance of grain size on deciding the set-up behavior, it can be well addressed by classifying soils into the fine- and coarse-grained categories.

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