Time-related Increase Evaluation in Bearing Capacities of End Bearing Jacked Piles by a New Type of CPT

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Abstract

The time-related increase in capacity of displacement piles after installation (known as set-up) is caused mainly by the shaft resistance. But the shaft and base resistances are seldom considered separately in the set-up evaluation. The time-related increase in capacity depends on the mobilization degree of the shaft capacity at the end-of-jack (EOJ), though this mobilization is closely related to the bas resistance. In this paper, a series of field tests including the jacking installation tests, load tests of model piles and a new type of CPT with a total resistance sensor installed were conducted at the Pearl River Delta alluvial plain. The tests have found that there are three type of distribution curves between the ultimate total shaft resistance and the measured one: the ultimate resistance is greater than, very close to or less than the measured one, and set-up is obvious in the first one, while in the other two are not. This indicates the mobilization of the shaft resistance at the end of jacking installation affects set-up. According to the experimental study, a new evaluation method has been proposed and proved reliably by practice, in which the mobilization of the shaft resistance is considered.

Keywords: Time-related Increase, Bearing Capacity, Jacked Pile, cone penetration test

1 Introduction

It is widely recognized that displacement piles typically undergo a time-related increase in capacity following initial installation. This phenomenon is called as "set-up" or "freeze" and has been first reported by Wendel (1900) [1]. Although rare, a time-related decrease (also known as "relaxation") in capacity has also been observed for piles installed in dilative soils or when lateral stress decreases after pile installation [2]. The set-up is initially associated with an increase in effective stress due to the dissipation of positive pore water pressure during primary consolidation [3-5]. The consolidation of soils may take several months in cohesive soils [6], whereas it is usually assumed to occur within 24 hours in highly permeable sands [7]. The consolidation period may be longer for displacement piles compared to non-displacement piles because of the large volume of displaced soil [8]. In addition, the liquidation of the loose, saturated granular soils is also the reason of set-up [9]. However, numerous case histories [7, 10-12] indicate that pile capacity will often continue to increase long after the dissipation of pore water pressure and this phenomenon is called aging. Bullock (2008) suggested that the consolidation and aging effects coincide in cohesive soils, resulting in continuous set-up [13]. Aging may be associated with soil restructuring [14], soil fatigue [15], corrosion of steel piles [16], clay dispersion, thixotropy, and secondary compression [17], and recementation in calcareous materials following installation [18]. The consideration of set-up effect can efficiently improve the estimation of pile capacity, so that the length, diameter or the number of production piles may be economically reduced. Therefore, many researchers focus on quantifying set-up with the short-term axial force at the end of drive or jack (EOD or EOJ), and lots of empirical equations have also been proposed to quantify the magnitude of set-up, most of which are summarized in Table 1.

These researches mainly focused on the driven piles in the early time. The jacked piles were limited by the installation machine greatly in that time and began to be studied continually until recent decades. The current study results shows that the base resistance almost remains constant under different installation conditions, therefore the time-related increase in capacity results from the shaft resistance mainly [11, 18, 26, 27]. Since it is so, the time-related increase of shaft resistance is different from that of the base resistance. The capacity should be divide into two parts when the time-related increase of pile capacity is evaluated. The induced pore water pressures are expected to be higher in the pile jacking installation with faster velocity, so a lower shaft resistance will be mobilized and the long-term capacity will be greater than the installation resistance [28]. That means the set-up effect is more obvious with faster velocity and the shaft resistance is variable during installation. Therefore, the mobilizing degree of shaft resistance at the end of drive(EOD) or jack (EOJ) will

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affect set-up effects obviously. However, this affect is rarely take into account in all of the empirical formulas mentioned in table 1. The mobilization degree of shaft resistance at the end of installation is considered stable for the friction pile in the homogeneous soil layers, but it will be variable obviously when the piles insert into a hard soil partings (such as the sand partings in clay) soil layer or a hard bearing stratum(such as a strong weathered rock stratum). Generally, the set-up effect is not obvious in end bearing piles because the shaft resistance cannot be mobilized. The full mobilization of the shaft resistance needs enough relative displacement, while there is little displacement in the end bearing piles. But when the bearing stratum is a weathered soft rock layer, the set-up effect varies significantly because there is a certain displacement causes the shaft resistance to be mobilized. From that has been discussed above, the mobilizing degree of shaft resistance at EOD or EOJ should be considered and the capacity should be divided into two parts when evaluating set-up.

TABLE 1 Empirical formulas for predicting displacement pile capacities

Author(s)	Equation	Comments
Skov and Denver (1988)[19]	$Q_t=\left[1+A\log(t/t_0)\right]Q_0$	Driven piles in sands, clays Qt = pile capacity at time t Q0= pile capacity at time t0 sand: t0 = 0.5 A =0.2 clay: t0 = 1.0 A =0.6
Huang(1988)[12]	$Q_t=Q_{EOD}+0.236\left[1+\log t(Q_{MAX}\text{-}Q_{EOD})\right]$	Driven piles in soft soil QEOD= pile capacity at EOD QMAX= maximum capacity of pile
Guang-Yu(1988)[20]	$Q_{14}=\left(0.375S_t+1\right)Q_{EOD}$	Driven piles in fine grained soil St = sensitivity of soil Q14 = pile capacity at 14 d
Bogard and Matlock(1990) [21]	$Q_t=Q_u\left(0.2+\dfrac{t/t_{50}}{1+t/t_{50}}\right)$	Driven piles in clay Qu = ultimate capacity with 100% set-up t50 = time corresponding to 50% set-up
Svinkin(1996)[22]	$Q_t=1.4Q_{EOD}t^{0.1}$ upper bound $Q_t=1.025Q_{EOD}t^{0.1}$ lower bound	Driven piles in sand
Long et al. (1999)[23]	$Q_t=1.1Q_{EOD}t^{0.13}$ upper bound $Q_t=1.1Q_{EOD}t^{0.05}$ lower bound	Driven piles in sands, clays, mixed soils
Svinkin and Skov(2000)[24]	$Q_t=\left[1+B\left(1+\log t\right)\right]Q_{EOD}$	Driven piles in sands, clays Derivation from Eq. of Skov and Denver (1988) t0 = 0.1 day B similar to A
Zhang(2009)[25]	$q_t=q_0\left(0.3\log t+0.28\right)$	Jacked piles in soft clays qt = unit shaft resistance at time t q0 = the unit shaft resistance at EOD
Deng et al. (2013)[26]	$Q_{ut}=Q_0(1+\eta_{ut})$ $\eta_{ut}=\dfrac{t}{a+bt}$	Jacked piles in sands, clays Qut = ultimate bearing capacity Q0 = ultimate piling force at EOJ (t = 0) ηut = increase in Qut relative to t Q0 (%) a, b = constants
Reddy and Stuedlein(2014) [27]	$Q_t=\dfrac{Q_0A\log\left(t/t_0\right)}{k_1+k_2Q_0A\log\left(t/t_0\right)}+Q_0$	Driven piles in sands, clays Derivation from Eq. of Skov and Denver(1988) k1 and k2 = fitting parameters

In this paper, a study on the time-related increase was conducted with the weathered soft rock chosen as the bearing stratum and the mobilization of shaft resistance taken into account. The mobilization degree of pile shaft resistance at EOD or EOJ can be predicted using the tests of a new type of cone penetrometer. Compared with the dynamic driving, the jacking process is a quasi-static process [29], which more similar to the cone penetration test (CPT), therefore the jacked model pile and its corresponding CPT were selected for comparative study in this paper.

2 Materials and Methods

2.1 TEST SITE SELECTION

If the base resistance of pile changes little when installation, the mobilizing degree of shaft resistance at EOJ changes little too. This is bad for the study of shaft resistance mobilezation, so several test sites have been chosen in the Pearl River Delta alluvial plain. Generally, the stratum in this area consists of more than 20 meters thick clay layers with sand partings in the middle and a weathered bedrock under it. So the jacked piles in this area are mostly end bearing piles. But the weathered bedrock is so heterogeneous that the base resistance is variable tempestuously when inserting into the bedrock, and causes accompanying variation of the shaft resistance mobilization. When the piles insert into the sand partings, the same variation of the shaft resistance mobilezation will occur too. This is helpful to the research work of this paper.

2.2 TEST EQUIPMENT AND TEST METHODS

To study the mobilization degree of shaft resistance at EOJ, the shaft resistance should been measured. It is too troublesome and inconvenient for practical engineering application to measure the shaft resistance and its changes at different time and depth directly during installation. So an auxiliary sensor of installation resistance have been installed on the traditional cone penetration. With this simple improvement, the actual total shaft resistance during the whole installation will be measured easily. The penetrability of cone penetration are also improved enough to penetrate into the strongly weathered bedrock. This new YJJT350 type CPT was invented by FoshanShunde survey and design limited company (Chinese patent number: 200420044-127.5, figure 1). As for the model pile, a closed-ended tubular steel pile with 300mm diameter is chosen. The instrument installed on the model pile is similar to the YJJT350 type CPT, a tip pressure plate, a side pressure plate, two side friction drums, and a sensor of installation resistance were installed on it.

The field test of model pile and the new type CPT are both done in the same site. The installation velocity of CPT and model piles are specified in 1mm/min and 2m/min respectively in order to eliminate the differences caused by velocity. The load test could be conducted with the pile jacking machine. The specific research steps are as following. First, the installation of jacked pile is compared with that of CPT in order to predict the mobilizing degree of pile shaft resistance at EOD or EOJ using CPT data. And then, the time-related increase in capacity is determined by model pile test. The relationship between the mobilizing degree and time-related increase in capacity is studied at last.

FIGURE 1 The new YJJT350 type cone penetration.

FIGURE 2 The field test of model pile.

3 Results and Discussion

3.1 THE TOTAL SHAFT RESISTANCE AND THE ULTIMATE TOTAL SHAFT RESISTANCE.

Through the test of model piles and the new type of CPT in the Pearl River Delta alluvial plain, a series of data results are obtained. The analysis and discussion in the below will be focused on the shaft resistance, because the shaft resistance is the key to elevate the set-up effect. The actual total shaft resistance of CPT can be calculated by following equation:

$$Q_{cs} = P - A_{cp} q_c \ , \tag{1}$$

where Qcs is the total shaft resistant of the cone penetrometer, P is the total force of the cone penetrometer, Acq is the cross-sectional area of the cone penetrometer rod, qc is the tip resistance of the cone penetrometer. The ultimate total shaft resistance of CPT can be calculated by following equation:

$$Q_{cs} = u \sum l_i f_{si} \ , \tag{2}$$

where fsi is the unit ultimate shaft resistance of i-th layer measured by CPT, li is the thickness of i-th layer and u is the perimeter of probe intersection. Thus, the curve of the actual shaft resistance and the ultimate total shaft resistance can be plotted in figure 3.

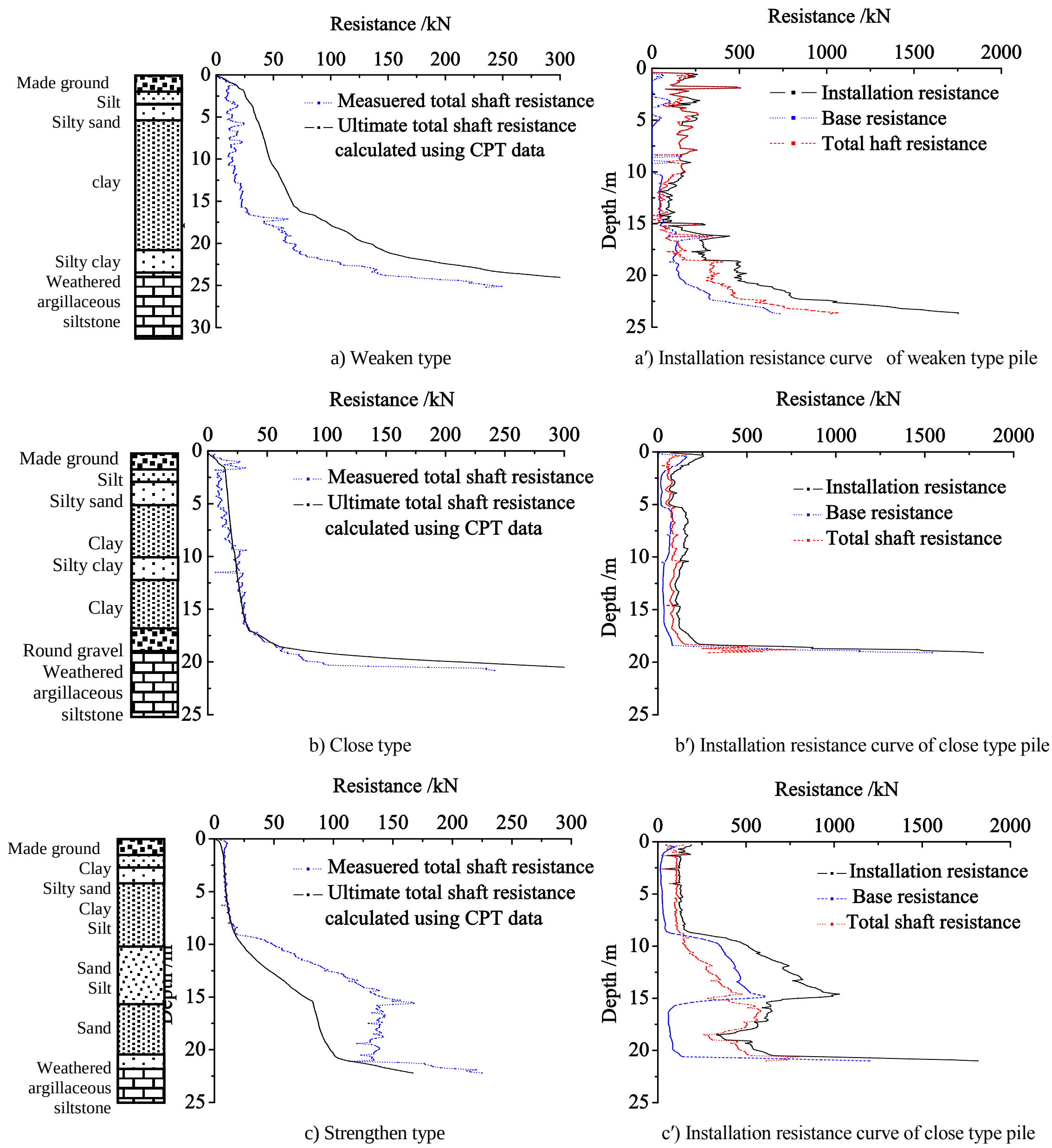

FIGURE 3 Three kinds of relationship between measured total shaft resistance and ultimate total shaft resistance calculated using CPT data and its corresponding installation resistance curves of model pile tests

TABLE 2 The set-up effects of three types of jacked pile in the Pearl River Delta alluvial plain

Type	**Resistance at EOJ**			**Load test after 14 days**			**Set-up effect**		
	Installation	*Base*	*shaft*	*capacity*	*Base*	*shaft*	*capacity*	*Base*	*shaft*
Weaken	1753	731	1021	2387	637	1750	1.36	0.62	1.71
	1800	1203	596	2639	1064	1574	1.47	0.88	2.64
Close	1827	1543	284	2010	1405	604	1.10	0.91	2.13
	1890	570	1320	1760	433	1265	0.93	0.76	0.96
strengthen	1815	1202	613	1760	1093	667	0.97	0.91	1.09
	1785	827	958	1760	871	888	0.99	1.05	0.93

3.2 THREE TYPES OF SHAFT RESISTANCE MOBILIZING MODELS

The CPT finds that there are three kinds of relationship between measured total shaft resistance and ultimate total shaft resistance calculated using CPT data (Figure 3). The first kind of relationship is called weaken type, which the measured one is less than the ultimate one (Figure 3a). The second kind of relationship is called close type which the measured one is very close to the ultimate one (Figure 3b). And the last kind of relationship is called strengthen type, which the measured one is greater than the ultimate one (Figure 3c).

The weaken type is the most common distribution pattern especially appeared in the friction piles. The set-up effect of this type of pile is very obvious (Table.1). This weaken phenomenon is caused by the increasing of pore water pressure and structure disturbance of lateral soils [26] or sliding friction[30-32] between the pile and the soils during installation. The time-related increase of pile capacity is essentially caused by the increase of shaft resistance. The weaken shaft resistance will restore to its ultimate resistance. The more the shaft resistance reduces during installation, the more the capacity increases with time after installation. The shaft resistance alone the whole pile length cannot reach its ultimate resistance at the same time because the relative displacement between pile and its lateral soil at different depth. The shaft resistance reaches its ultimate value only at part of the pile length, and the most troublesome thing is that the shaft resistance mobilization of the other part of pile length is different at the same time. This leads to the difficulty to estimate the shaft resistance precisely. So in this paper, the author thinks that it is not proper to calculate the total shaft resistance by the accumulation of every soil layers, especially during pile installation. The installation purpose of the total resistance sensor on the cone penetrometer is to measured shaft resistance directly. Thus the time-related increase in pile capacity can be estimated by the comparison of the corresponding increase in CPT.

There is almost no set-up effect for both of the other two types (Table.1). In the case of the close type, the dissipation of the pore water pressure should be fast, but the lateral soils of the pile mainly is clay. It is more incredible that the actual total shaft resistance of CPT is great than the ultimate one calculated using the traditional CPT data. These phenomena cannot explain reasonably with the traditional the theory of dissipation of pore water pressure and soil restructuring.

3.3 ANALYSIS OF THE SHAFT RESISTANCE MOBILIZING MECHANISM

From the view point of tribology, friction, lubrication and wear [30, 31] occur at the same time on the pile-soil interface. The material of the pile is harder than soils, so lots of soil fragment is plowed down by the asperities on the pile surface and mix with the water squeezed out from the soil around the pile when installation to form an unstable layer of mud. The lubrication of this unstable mud layer leads to the decrease of the shaft resistance. According to the tribology, the friction between pile and the unstable mud layer can be calculated by following equation [28]:

$$f_s = \tau_l = \frac{\eta_l V}{h}, \tag{3}$$

where fs, τl are the friction force and shear force, ηl is the viscosity of the unstable mud layer, V is the installation velocity of jacked pile, h is the thickness of the unstable mud layer.

Therefore, the friction is associated with the thickness, the viscosity of the unstable mud layer and the relative velocity between the pile and the unstable mud layer. In fact, this factors are variable in the installation of jacked pile. The thickness is concerned with the characteristics of the soils around the pile and the plowing effect of the asperities on the pile surface. The soils near the ground are plowed longer than that near the end of pile, so the thickness of the unstable mud layer is usually thicker near the ground. And the unstable mud layer is usually thinner in the harder soil than that in the softer one. The viscosity is usually concerned with the installation velocity of the jacked piles.

When the pile is jacked continuously at a constant velocity or an increasing velocity, there is so much water is squeezed out from the soil around the pile that the mud layer contains too much free water and its viscosity is closed to water. But the jacking velocity slows down when the pile is jacked from a soft soil into a hard ones. In this case, the free water in the mud layer will soon be absorbed by the soil around the pile and the viscosity of the mud layer will increase. The soil around the pile is just like the sponge, when it is squeezed, the water will be squeezed out, but when the extrusion force on the soils decreases, the squeezed-out water will be absorbed into soils for the difference of pore water pressure. Therefore, the total shaft resistance increases with the base resistance increase, as shown in figure 3 (a′), (b′) and (c′), this increase is caused by the reduction of the free water in the unstable mud layer. This reduction of the free water causes the viscosity increase of the unstable mud layer, and thus the shaft resistance increases. However, the increase of the total shaft resistance occurs only in a certain degree. If the bearing stratum is so hard that few relative displacement generates, the total shaft resistance will decrease, as shown in figure 3 (a′), (b′) and (c′).

On the basis of what has been discussed above, the mechanism of the three type of shaft resistance distribution can be explained. For the weaken type, the soils around the pile are relatively weak, so the pile can be jacked in a stable installation velocity. The soils around the pile are squeezed continuously and too much water is provided to form a mud layer which is full of free water, so the actual total shaft resistance is less than the ultimate one. For the close type, all of the squeezed-out water is absorbed back to the soils around the piles, so the actual total shaft resistance is close to the ultimate one. The soil around the pile is compacted continually when the pile is jacking at a constant velocity, but when the velocity slows down, the soil around the pile will expand and lead to a negative pore water pressure which can absorb the water back from the side of the pile. For the strengthen type, there is a sand layer in the middle of the embedded depth (figure 3c), the unit shaft resistance increases gradually with the continual compaction of the sand layer when the jacked pile penetrates gradually into the sand layer. The continual compaction of the sand layer can also make the jacking velocity to slow down, the free water will absorb back to the soil around the pile and the shaft resistance will increase. When the pile penetrates through the sand layer and then into the silt layer, the total shaft resistance increases with the decrease of base resistance. But when the base resistance decreases to a lower level in the depth of about 16m, the total shaft resistance begins to decrease subsequently. When the pile end reaches the depth of 18m, the total shaft resistance begins to increases again with the increase of base resistance. Until the base resistance increases to a high level, the total shaft resistance begins to decrease. These complicated changes of the shaft resistance is concerned with the changes of the base resistance which will first affect the installation velocity, change the viscosity of the unstable mud layer and then influence the shaft resistance. So the shaft resistance is closely related to the characters of the unstable mud layer. Figure 3 (a′), (b′) and (c′) also shows that the base resistance of (b′) and (c′) increases more sharply and its curves similar to a horizontal line. This means that the base resistance is more important in the capacity of the pile of (b′) and (c′).

According to the analysis above, evaluating the time-related increase of pile capacity should consider the mobilizing degree of the total shaft resistance at the end of jack, especially when the pile is the end-bearing one, such as the piles in the in the Pearl River Delta alluvial plain. The time-related increase of pile capacity is associated closely with the unstable mud layer.

3.4 APPLICATION OF THE MOBILIZING DEGREE

On the basis of the analysis above, a coefficient called mobilization degree of the total shaft resistance η is introduced and used to estimate the time-related increase of pile capacity. If the shaft resistance mobilization model is the weaken type, then the mobilization degree of the total shaft resistance η can be derived from equation (1) and (2):

$$\eta = \frac{P - A_{cp} q_c}{u \sum l_i f_{si}}, \tag{4}$$

Else if the shaft resistance mobilization model is one of the other two model types, then η=1. The average of the total shaft resistance η near the pile end can be calculated using the data of the new CTP introduce in this paper.

Considering the size effect between CPT and the pile, if the shaft resistance mobilization model is the weaken type, then the time-related increase of pile capacity can be evaluated by following equation:

$$Q_t / Q_0 = \frac{\alpha u_p \sum l_i f_{si} + \beta A_p q_c}{\alpha \eta u_p \sum l_i f_{si} + \beta A_p q_c}, \tag{5}$$

where Qt is a medium-term capacity, α, β is the correction coefficient of the size effect between CPT and the pile, Ap is the cross-sectional area of the pile and up is the perimeter of the pile intersection. Else if the shaft resistance mobilezation model is one of the other two model types, then:

$$Q_t / Q_0 = 1 \tag{6}$$

The field tests in this paper are conducted in the Pearl River Delta alluvial plain and the load tests is finished 14 days after the jacking installation. According to the tests result in this paper, the correction coefficient α, β is very close to 1. The equation has been applied in the other sites of the Pearl River Delta area in where the piles are always end-bearing type one and has been proved reliably to the end-bearing jacked piles with a close diameter. But when applied to the other type of piles (such as friction piles) with the other diameter in the other type of area, the correction coefficient α, β and the applicability of equation (5) should been further studied.

4 Conclusion

In this paper, a serials of tests has conducted including the installation tests and the subsequent load tests of the full scale model piles and a new type of CPT. On the basis of the results of the field tests and the mechanism analysis, the conclusion is summarized below:

(1) The results of the new CPT introduced in this paper shows that there are three types of shaft resistance mobilezing models: weaken, close and strengthen type. The weaken type is of obviously time-related increase in pile capacity, while the others are not.

(2) The mechanism analysis from the view point of tribology shows that the key influence factor to the shaft resistance of pile is the unstable mud layer around the pile, especially in the end-bearing piles such as that in the Pearl River Delta area.

(3) On the basis of the researches, a new time-related Increases evaluation method in the bearing capacities of end-bearing jacked piles using a new type of CPT is introduced and proved precisely in the Pearl River Delta area. But for the piles with other diameter in another area, the correction coefficient α, β should be further studied.

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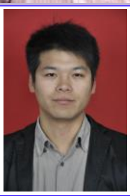

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