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**Review of the shaft capacity degradation of bored piles
constructed with bentonite slurry**

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REVIEW OF THE SHAFT CAPACITY DEGRADATION OF BORED PILES CONSTRUCTED WITH BENTONITE SLURRY

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ABSTRACT

Over the last few decades, different researchers have studied the influence of different construction parameters on the shaft load transfer of bored piles constructed with slurries. Still the issue is not fully resolved, different parties involved in the bored piling industry believe on the degree to which these parameters effect the perimeter load transfer. This paper attempts to summarize all the significant works previously done on this subject. It is concluded that the realistic formulation of specifications and selection of design parameters with the consideration of practical constraints at site is very important. Performance of the bored piles is effected by installation procedures, all the ill effects attributed to the construction parameters can be eliminated by following good engineering practices.

INTRODUCTION

It is commonly accepted that the construction parameters like slurry properties, construction time, equipment used, etc., effect the performance of wet process bored cast in-situ piles. But the extent to which these parameters effect the pile capacity is not clearly understood due to the wide variation in the soil conditions and other influencing factors which are simultaneously acting. It has also been recommended in some codes of practice that observing good engineering practices can eliminate all the foreseeable ill effects attributed to these parameters.

CONSTRUCTION PARAMETERS

Among the other various parameters, construction time and slurry properties are particularly considered responsible for the degradation of the pile shaft capacity. In fact the total construction time is not directly related to the pile performance. Critical time, which might contribute to the degradation of the pile, starts after the borehole excavation is completed till the completion of the concrete pouring. Time consumed in the excavation operation is not generally considered to contribute any degradation since slurry is continuously kept agitated during drilling operation. A maximum elapsed time of 24 hours after the completion of the borehole excavation is generally recommended under normal conditions. Slurry properties especially the viscosity is believed to be another important factor related to the quality of the constructed pile, because it determines the degree of replacement by concrete during tremie concreting.

Previous published researches on this issue along with the brief conclusions made are given in the following in a chronological order.

Chaidesson (1961) observed a better load-settlement behavior for one pile drilled with slurry than the other pile drilled by a casing method.

Corbett et al. (1970) presented the results of load testing of test panel excavated under bentonite slurry, excavation took 2 days and on completion the panel was left open overnight, but bentonite was renewed prior to concrete. The authors inferred that the presence of bentonite suspension even for such a long time was not adversely affected the development of skin friction.

Farmer, Buckley & Sliwinski (1970) conducted the laboratory tests on model concrete pile. The results indicated that presence of a bentonite filter cake at the concrete/sand interface has little effect on load transfer. Full scale tests on three deep bored piles constructed under bentonite, indicated that the load transfer was extremely higher than the expected. They concluded that high load transfer level may be obtained from piles constructed under bentonite, this may be due to uneven side-wall configuration.

Reese & Tauma (1972) found that the values of load transfer developed in clayey soils on the sides of the shaft constructed by the slurry displacement method are comparable to those in the shafts constructed in the dry.

Wates & Knight (1975) concluded from their investigation that a bentonite filtercake of a significant thickness would develop in 24 hours. In order to prevent a build up of filtercake, the slurry should be left in place much less than 24 hours.

Cernak (1976) performed full scale load test on three barrettes in sandy gravels. Two of the barrettes were constructed using slurry with different exposure times (8 and 97 hours) and their load test results indicated a decrease of skin friction capacity of 43% and 56% respectively, as compared to the other barrette excavated dry and concreted immediately. It must be noted that the major part of the reduction i.e. 43% took place in the first 8 hours of construction time while only 13% (56-43) reduction took place in the rest of 89 hours (97-8) for the second barrette. These findings support the conclusion of Wates & Knight (1975).

Sliwinski (1977) reported that displacement of suspension of slurry from the sides of the bored hole does not constitute a major problem. The rising column of concrete will displace the fluid suspension because of the considerable difference in unit weight and shear strength of the materials. The author stated that the field and laboratory tests seem to indicate that the influence of some bentonite in the parent soil has an insignificant influence on load support providing that the properties of the slurry are within reasonable limit and the concreting is done within a reasonable short time after the excavation is completed.

Fleming & Sliwinski (1977) reported on 49 filed tests from several countries. The test results suggest that the use of bentonite suspension has no detrimental effect on shaft friction while in granular soil, there is an indication that skin friction at high displacement may be slightly be reduced, though there may be reasons unrelated to the bentonite process. They suggested that concreting should be completed within 24 hours of the completion of boring.

Reese & Tucker (1985) concluded that the capacity of bored piles constructed under slurry could be substantial with proper construction technique. The slurry will be ejected from the excavation and substantial bond will develop at the interface of the concrete and the supporting soil. However, the authors also suggested that the slurry must not be left more than few hours in the excavation without operation of drilling tool; otherwise, a thick filter cake will develop on the side of the excavation.

Reese & O' Neil (1988) suggested that a solution to the problem of reduced skin friction due to excessive filter cake is to maintain the properties of the slurry within tolerable limits and to place the concrete the same day that the excavation is completed. If for some reason, it is impossible to place the concrete without undue delay, the drilling machine must be re-occupied the excavation to rework the borehole. If the slurry remains for a period of time without agitation, the filter cake can become thick.

Fleming et al. (1992) concluded that the process of forming a pile under bentonite suspension does not materially reduce the shaft friction in both granular soil and cohesive soil. The rising column of concrete with a slump in excess of 175 mm from tremie process will largely remove the filter cake layer on the wall surface of shaft. However, if the hole is left filled with slurry for long period (no agitation action), this will give rise to a significant reduction in shaft friction on completed piles.

O'Neil & Reese (1992) reported the effect of slurry properties on two drilled shafts constructed in similar ground conditions (alternating layer of very stiff clay and dense sand). Shafts 1 and 2 were constructed with Marsh cone viscosity of 37 and 49 sec respectively. Time between opening the borehole and completion of concreting for both piles was 5 to 7 hours. Minor difference in load transfer of both shafts was found and the authors concluded that the difference in slurry properties used for the construction for both shafts had a little effect on shaft load transfer.

Wardle et al. (1992) concluded from four piles tested in London that the axial capacity of driven and jacked piles after one or two months were 14 to 28% greater than those measured during or immediately following installation. CRP tests performed after about 3 years recorded further increase of between 14 to 20% (total became 28 to 48%). Although, it was not possible to record the capacity of the bored pile immediately after installation, the capacity of this pile increases by 47% between 2 months and three years.

Majano & O'Neil (1993) attempted to model the formation of filter cake in the laboratory with different slurry dosages, differential pressures and exposure times. They stated that perimeter load transfer is a complex function of the physical and chemical characteristics of the slurry and the geomaterials, the roughness of the borehole, the fluid pressures exerted by concrete, the shearing properties of the soil, and possibly the chemistry of the fluid concrete. They attempted to correlate the potential degradation of the soil-pile interface to the thickness and shear strength of the cake formed against the walls, and argued that the shear strength and thickness can not be measured with only one or two parameters like slurry dosage and differential pressure. With a bentonite concentration of 72 kg./m³ and differential pressure of 0.5 psi, they achieved a filter cake thickness of 3.14 and 4.5 mm after a contact time of 4 and 24 hours. Authors also compared the laboratory tests with the actual field conditions and proved that due to the presence of enormously high differential pressures in the field in some cases, thickness of filter cakes which would be considered detrimental for shaft load transfer, require few hours to develop (Authors proved that a filter cake of 6 mm. thickness would require only 2.3 hours to develop in the field under a differential pressure of 10 psi).

Hosoi et al. (1994) reported that when the diaphragm wall foundation is cast in slurry, mud cake could not be fully scoured by concrete. So the evaluation of the shaft friction mobilized on the wall foundation cannot overlook the effect of mud cake. They concluded from laboratory tests that the friction resistance between concrete and the sample soil (decomposed granite) through bentonite slurry cake is smaller than the shear strength of the sample soil.

Ho & Lim (1998) reported that the barrette sized 2.8 m x 0.60 m x 47.4 m excavated under bentonite slurry support at Singapore Post Center project with a total construction time of about 110 hours has been tested. The test result showed that substantial shaft friction could be mobilized to carry load satisfactory with a reasonable factor of safety and within a tolerable displacement of 12 mm at working load.

Littlechild & Plumbridge (1998) presented that the values of actual shaft resistances mobilized for in the five pile load test carried out at BERTS project and compared to the calculated shaft resistances, where calculated shaft resistance is based on the design approach adopted on the project. For cohesive soil $f_s = \alpha C_u$, α taken as 0.5 for stiff and hard clay

layers and for sand layers shaft resistance of 120 KPa has been determined for all sand layers. Construction time and slurry viscosity on this project was controlled to be less than 24 hours and 35 sec respectively. They concluded that shaft friction capacity of bored piles constructed under bentonite slurry tends to decrease as the construction time and slurry viscosity increases.

Thasnanipan, Baskaran & Anwar (1998) presented the shaft friction values mobilized from eleven instrumented bored piles constructed under slurry with different construction times and bentonite viscosity from various sites in Bangkok area. They concluded that the slurry viscosity up to 55 sec./Qt do not have significant effect on the shaft load and degradation of shaft capacity with increase in construction time beyond 24 hours is not excessive.

DESIGN CONSIDERATIONS AND PARAMETERS

Selection of design parameters, which suits the local construction practices and procedures, is very important. Design parameters are normally selected based on the previous researches of local institutions/organizations along with some special considerations specific to the sites. Following are the recommendations and suggestions that need to be observed for the estimation of shaft load capacities in Bangkok subsoils.

Sliwinski and Fleeming (1974) suggested that in clay soil, the bentonite has no effect on friction and no reduction of the normal factors for deriving adhesion is justified. There may indeed be a slight increase of adhesion. In granular soils, the bentonite has some effect. The reduction of friction calculated from effective lateral pressure and coefficient of friction should be considered in the region 10-30%.

Oonchittikul (1990) back analyzed a parameter $\beta = (K_s \cdot \tan \phi)$ from instrumented bored pile load tests conducted with bentonite slurry in Bangkok subsoils by using the effective stresses with both the hydrostatic pore pressure and the declined pore pressure. The resulted β value in the first and second sand layers from effective overburden pressure based on hydrostatic pore pressure falls in the range of 0.4 to 0.65 and 0.2 to 0.4 respectively while β value in the first and second sand layers from effective overburden pressure based on declined pore pressure falls in the range of 0.1 to 0.48 and 0.1 to 0.2 respectively. In both cases β value in second sand layer is less than the value in the first sand layer. The author inferred that the overburden pressure might not fully develop at great depth in sand layer as it has been assumed in the calculations.

Hooley & Brooks (1992) have suggested that if the traditional pile design approach is used, the proper interpretation must be given to the accuracy of the data employed by soil investigation as the potential error in the calculation of ultimate base resistance increases steadily with depth and shaft resistance error increases gradually with depth. The authors reported that it is noticeable that the amount of scatter in the test result from soil investigation samples increases with depth and thus the average line is more difficult to define at greater depths. If the scatter is analyzed statistically, upper and lower bound of average line can be identified on the basis of chance of error 0.01% probability.

Eide & Bellis (1992) extracted data from 13 numbers of loading tests taken to failure from the test results of over 109 tests in Bangkok which are presented by Oonchittikul (1990). The authors found average shaft friction in stiff clay and dense sand in the range 78 to 130 KPa and adopted 100 KPa as design value, which is commonly used for design in Bangkok Subsoil.

Teparaksa (1992) reported the problem from bentonite sedimentation causes a soft base. Unexpectedly, low skin friction can be mobilized at failure (design at yield point) in soft base condition. The author also reported that the static load test results on 1.50 m dia. pile at Pok

Klao bridge project in Bangkok indicates an excessive settlement at 4000 KN load which is caused by deposition of bentonite at the base of the pile. Analysis of load transfer indicates that the skin friction of first stiff clay, first sand, and second stiff clay are equal and about 40 KPa at 4000 KN load. After the base grouting with cement-mortar, the analysis shows the skin friction of this soil is between 40 to 90 KPa at about 5 mm. movement. They are in the expected range for each soil layer, which is not affected by grouting.

Meißner et al. (1993) studied the influence on bearing behavior of bored piles when the pile base is approaching a layer of soft soil layer and concluded that a significant punching mechanism is obtained for value of $t/d = 2$, where t is the distant from pile base and the clay layer and, d is the pile diameter. This punching mechanism would decrease significantly both shaft and base resistance.

Tomlinson (1996) suggested that if pile is excavated by grab under water, there is considerable loosening of the soil. This causes a marked reduction in both end bearing and skin friction. Then the design calculation will be calculated on the basis of a low relative density of the granular soil.

Littlechild et al. (1998) reported that the shaft resistance of both the plain and shaft grouted bored piles in sand appears to be mostly independent of the vertical effective stress over the stress range encountered. From the test result of plain bored piles constructed in accordance with a given specification of BERTS project in Bangkok i.e. bentonite viscosity <35 sec and construction time of less than 24 hours, the shaft resistances fall in the range 65 to 170 KPa. In addition, they have determined a design line for shaft resistance of plain bored piles in Bangkok sand of 120 KPa for all ranges of vertical effective stresses.

Thasnanipan et al. (1998) revealed that the end bearing capacity of bored pile where toe is embedded in to the clay layer would be reduced and this end bearing capacity reduction might influence the shaft resistance capacity too. This conclusion was reinforced by the pilot pile load test result in the project located on Rama III road in Bangkok having diameter 1500 mm, toe founded at 60m in clay layer, failed at only about 17500 KN with total settlement of over 90 mm. While the designed maximum test load was 25000 KN compared to the pile load test from contract pile of same diameter toe depth founded in sand layer at depth 55 m and base grouted. Result of test up to 2500 tons with total settlement of only 29.26 mm and elastic recovery was 17.52 mm recorded.

CODES AND SPECIFICATIONS

Specifications are prepared for the good of the project. Specs drafted by ignoring the practical site constraints and specific project needs can cause a job to become problem for all parties. For example, some specs have been found to stressing on maximum allowable construction time of 24 hours, which sometimes become impossible to adhere to because of the prevailing traffic congestion in the city centers and local authority regulations in Bangkok, and ultimately instigate the contractor to breach the law in order to comply with such unpractical specs. A summary of the slurry specifications used worldwide is given in Table 1. In the following are given some suggestions related to the excavation under bentonite slurry.

Fleming et al. (1975) suggested that the specifications should set out a cause of action to perform the work, which is reasonable from the contractor's point of view and gives a reasonable expectation of achieving the desired end product. A specification loses credibility on site if its requirements are outside the range of practical achievement and such a specification can only be detrimental to the whole job. They further suggested that obscure requirements will naturally be the first to be forgotten. Thus, for example, it is better to say "after mixing concrete shall be placed before it lose the specific workability" than to say "concrete shall be placed within X minute (s) from mixing".

Littlechild & Plumbridge (1998) reported that the majority of the piling contractors state that a maximum construction time for bored pile constructed to depth 50m under bentonite slurry for BERTS project in Bangkok of less than 24 hours per pile would not be realistic. A maximum construction time of 24 hours and slurry viscosity of less than 35 seconds (use of Bentosund bentonite only) were therefore adopted for the project.

Chodorowski & Duffy (1998) presented the typical control and progress charts for 24 hours limit on construction time of bored piles at BERTS project, Bangkok. Charts prepared by the authors show that during the 24 month period of bored pile construction, there was noticeable percentage of pile constructed longer than 24 hours of approximately 15% which in some months as much as 30%. They reported that longer construction time of more than 24 hours per pile was due to difficulties in securing continuous concrete supply as a result of traffic congestion in the area of different piling sites.

Table 1: Summary of recommended values of slurry properties used for bored piles.

<i>Authors</i>	<i>FP S</i>	<i>Hutchin</i>	<i>Hodgso</i>	<i>Holden</i>	<i>FDOT</i>	<i>Rees</i>	<i>ICE</i>	<i>ACI</i>	<i>AASHTO</i>	<i>Majano</i>	<i>ICE</i>
<i>Parameter</i>	<i>1975,</i>	<i>et al.,</i>	<i>n</i>	<i>1984</i>	<i>1987,</i>	<i>&</i>	<i>1988</i>	<i>1989</i>	<i>1992</i>	<i>O'Neil</i>	<i>FPS</i>
	<i>1977</i>	<i>1975</i>	<i>1977</i>		<i>1988</i>	<i>O'Neil</i>				<i>Neil</i>	<i>ARUP</i>
						<i>1988</i>				<i>1993</i>	<i>1996</i>
Slurry Type	Bentonite	Calcium Bentonite	Bentonite	Sodium Bentonite	Bentonite or Attapulgit	Bentonite or Attapulgit	Bentonite	Bentonite or Polymer	Bentonite or Attapulgit	Bentonite	Bentonite
Density (gm/cc)	<1.10	1.024 to 1.218	1.024 to 1.135	1.03 to 1.20	1.03 to 1.20	1.03 to 1.20	<1.10	<1.36 Friction Shaft	1.03 to 1.10 1.03 to 1.20	1.02 to 1.07 1.02 to 1.13	<1.10 <1.15
pH	9.5 to 12	<11.7	10.8 to 11.7	8 to 11	8 to 12	8 to 11	9.5 to 12	8 to 12	8 to 11 8 to 11	8 to 10 8 to 10	9.5 to 10.8 9.5 to 11.7
Sand Content	<6% (by weight)	<35% (by weight)	<14% by volume (5% max. by weight)	10% max. (by volume)	<4% (by volume)	-	-	<25% (by volume Friction Shaft)	<4% <4% (by volume)	<4% <10%	<2% <2%
Marsh Funnel Viscosity (sec)	30 to 90	-	-	30 to 40	28 to 40	28 to 45	30 to 90	26 to 50	28 to 45 28 to 45	32 to 60 32 to 60	30 to 70 < 90
Plastic Viscosity (cP)	<20	<20	3 to 20	<20	<20	-	<20	-	-	6 to 8.5 6 to 10.0	-
Yield Point (Pa)	-	-	-	4.2 to 41.8	-	-	-	-	-	2 to 6.0 2 to 6.5	-
10 min. Gel Strength (Pa)	4 to 40	3.6 to 20	10 to 40	2 to 10	1.9 to 10	-	4 to 40	-	-	-	4 to 40 4 to 40
Differential Head (m)	>1	-	-	1 to 1.5	-	-	-	1.5	-	-	-
Fluid Loss (30 minute test)	-	-	-	-	-	-	-	-	-	-	< 40 <60
* Maximum Contact Time (hr.)	-	-	-	-	-	-	-	-	-	4	-

* Without agitation and side-wall cleaning

Note: For two rows in each cell (last three columns)
 First row: fresh or recycled as supplied to borehole
 Second row: prior to concrete pouring

ADSC and DFI drilled shaft inspector's manual clause 4.5.1, advised that where bentonite slurry remains in the shaft unagitated for 3 or 4 hours, or more than 24 hours even though agitated, a mud cake may develop on the shaft walls which can reduce friction. Unless, the designer has accounted for 'caking' and appropriately reduced design friction value or the specification gives other limitation, portion of the shaft or socket designed for side friction should either be excavated and concreted within a 24 hours period (and no more than 3 hours when the slurry is not agitated) or re-reamed or re-scraped to remove the mud

cake prior to concreting, or some method which is acceptable to the geotechnical engineer and the inspector used to demonstrate that detrimental mud caking has not occurred.

ADSC Specification Clause 2.3.5.2 (g) specified that the drilled pier constructed under bentonite slurry should be concreted and completed the same day that of excavation. If this is not possible, the excavation shall be re-drilled, cleaned and slurry tested before concreting. Shaft friction could be mobilized to carry load satisfactorily with a reasonable factor of safety and within a tolerable displacement of 12 mm at working load.

FHWA guide for drilled shaft specification, stipulates that, that drilling slurry is an effective method of stabilizing drilled shaft excavation until either a casing has been installed or concrete has been placed. Primary concerns connected to slurry use are: the shape of the borehole would be maintained during the excavation and concrete placement; the slurry does not weaken the bond between the concrete and both the natural soil and rebar; all of the slurry is displaced from the borehole by the rising column of fresh concrete; and any sediment carried by the slurry is not deposited in the borehole. The engineer’s concerns regarding the behavior and effectiveness of slurry project, can be satisfied by appropriate specification requirements. These requirements include: specifying a suitable range of slurry properties both prior to and during excavation and prior to concreting; performing slurry inspection test; and construction of pre-production trial shaft by the slurry method.

FULL SCALE TEST TO ASSESS THE EFFECT OF CONSTRUCTION PARAMETERS

Since the degree of effect of different parameters greatly depends upon the soil properties encountered, conclusions made for one type of soil are not directly applicable to other locations with different geology. Static, instrumented load test program on bored and barrette pile conducted at BECM tower project Rama IX road, Bangkok, provided the unique chance to determine the effects of construction parameters on the shaft capacity (Thasnanipan et al., 1999). Bored pile 1.5m diameter and a barrette 1.5x3.0m in cross-section had same lengths of 57.5m founded in the second sand layer and located 30m apart having similar soil embedment conditions. Properties of the bentonite slurry used are given in Table 2.

Table 2. Comparison of bentonite slurry properties for test pile and barrette.

Properties	Pile		Barrette	
	Before feeding to the borehole	After Recycling & Before concreting (near borehole base)	Before feeding to the trench	After Recycling & Before concreting (near trench base)
Viscosity (sec)	33	36	36	49
Density (g/cc)	1.08	1.10	1.10	1.17
pH value	8	8	8	9
Sand Content (%)	0.1	0.8	1.0	1.1

Total construction time for the bored pile and barrette was 27 and 75 hours, respectively. However, the total elapsed time between the final excavation (re-drilling & cleaning) and concreting for the pile and barrette was 16.25 and 20 hours, respectively. In spite of considerable difference in the total construction time and slurry viscosity, values of unit shaft friction mobilized in different soil layers did not show any difference in the shaft load transfer characteristics. This proves that the total construction time is not a crucial parameter, which effects the shaft load capacity if good engineering practices like re-drilling the borehole is applied.

CONCLUSIONS

Conclusions of various researchers can be summarized as follows:

- Bentonite viscosity up to the normally recommended range i.e. 60 sec., given in Table 1 does not have any significant effect on the skin friction capacity of bored piles. In authors' point of view, filter loss is the more relevant property of the slurry, which directly effects the formation of the filter cake and finally results in the shaft capacity reduction rather than the viscosity.
- Selection of pile design parameters with due consideration of site constraints is equally important. Adequate strength reduction factors based on the local experiences suggested by local research institutions need to be considered.
- Concreting should be completed within 24 hours after the finishing excavation of borehole. If due to some unavoidable reasons borehole is left filled with slurry beyond 24 hours with out agitation, re-drilling must be carried out to scarp off any filter-cake present on the walls of the borehole.
- Performance of bored piles, to a large extent, depends upon the installation procedures and, the skill of the operating crew, if proper construction procedures have been followed all the negative effects can satisfactorily be eliminated.
- It must be emphasized that the specifications for each project must be tailored to suit the actual site conditions keeping in view the constraints like possible delays in concrete supply due traffic congestion, local authority regulations etc. Among the available control limits for bentonite slurry shown in Table 1, this is authors opinion and experience that AASHTO specs are practically more suitable for pile excavation works in Bangkok subsoils.

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