Study of Effects of Construction Methods on Performance of Drilled Shafts

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***Abstract:*** Different methods of boring are in vogue for the construction of drilled shafts in the world. The most commonly used methods include rotary drilling, rotary bucket auger, percussion and continuous flight auger etc. It is widely reported in the literature as well as supported by some design codes that the load carrying capacity of drilled shafts depends a lot on the local construction practice in addition to soil parameters. In Pakistan, recently about twenty thousand drilled shafts have been constructed for the first ever Metro Electric Train and RLNG power projects. A host of boring methods have been used in their different contract packages, for drilling in wet as well as in dry conditions. The subsequent performance of full-scale static load tests on selected drilled shafts has divulged variable load carrying capacities for drilled shafts constructed by different techniques. This paper is based on a study of different factors involved during the construction of drilled shafts by different methods and their effect on load carrying capacity as ascertained from pile load tests. Practical conclusions have been drawn and recommendations have been made for the sound construction of drilled shafts in alluvial conditions as in Punjab Province, Pakistan.

***Keywords*:** Drilled shafts performance, rotary bucket auger, reverse rotary, pile load tests

**1. Introduction**

The improvement in pile construction practices in Pakistan has led to an increased reliance on different methods of boring for the construction of drilled shafts. The most commonly used methods include rotary drilling, rotary bucket auger, percussion and continuous flight auger etc. The Pile load testing is a part of design confirming in piling practice in the world. These tests provide valuable information regarding load-deformation behaviour of the prototype pile foundations. It is widely reported in the literature as well as supported by some design codes that the load carrying capacity of drilled shafts depends a lot on the local construction practice in addition to soil parameters [1-4]. About twenty thousand drilled shafts have been constructed for first ever Metro Electric Train and RLNG power projects in Punjab Province, Pakistan using a host of different boring methods, for drilling in wet as well as dry conditions.

Metro Electric Train is the first mass transit project of its kind which is being constructed in the metropolis of Lahore. The elevated portion of metro route is supported on pile foundations in alluvium. Three RLNG Power projects have been recently constructed in alluvial soils at three different sites including Bhikki, Balloki and Jhang where pile foundations were suggested as optimum foundation system for heavily loaded power plant structures in addition to mat foundation.

In order to verify the load carrying capacity of drilled shafts, before construction of actual working drilled shafts, ultimate pile load tests were carried out. The results of these load tests were used to finalize the drilled shafts design capacities. From experience of review of design and load testing of piles in alluvial soil conditions as in Punjab Province, Pakistan, the authors have attempted to study different factors involved during the construction of drilled shafts by different methods and their effect on load carrying capacity as ascertained from pile load tests. This paper tends to compare theoretically predicted loads and interpreted loads from pile load tests to describe the influence of methods of construction on the load carrying capacity of drilled shafts and frames recommendations for sound construction of drilled shafts in similar ground conditions.

**2. Subsurface Geotechnics**

Subsurface conditions from Metro Electric Train and RLNG power projects sites have been selected for this study. Soil parameters have been adopted for testpile design based upon the analysis of field data,

laboratory tests results, engineering judgement and experience in similar soil conditions.

**2.1. Metro Electric Train Project Site [5]**

Subsoil conditions enroute, consist of alluvial deposits comprising 5-7 m thick top layer of firm to medium-stiff silty clay followed by medium dense to dense silty sand/sand with silt stratum. Groundwater table depth varies from 15 – 22 m in general below existing ground level. The subsoil parameters provided in Table 1 were used for evaluation of pile capacities.

Table 1: Design soil parameters for project testpiles location

|  |  |  |
| --- | --- | --- |
| Depth (m) | Material Type | Selected Parameters |
| 0-3 | Fill | - |
| 3-5 | Silty Clay | Cohesion (c) = 30 kPa  Bulk Density γb= 17.0 kN/m3 |
| 5-33 | Silty Sand | Phi(φ) = 30o  Density (γb)=17.5 kN/m3 |
| 33-50 | Sand with Silt | Phi(φ) = 32o  Density (γb)=18.5 kN/m3 |

**2.2. Balloki RLNG Power Project Site [7]**

Subsoil conditions consist of alluvial deposits comprising top layer of firm to stiff silty clay/lean clay up to thickness of 8 m. This stratum is followed by dense silty sand/ poorly graded sand with silt. Ground water table depth varies from 3.3 to 4.4 m below existing ground level. Table 2 shows the subsoil parameters for evaluation of pile capacities.

Table 2: Design soil parameters for project testpiles location

|  |  |  |
| --- | --- | --- |
| Depth (m) | Material Type | Selected Parameters |
| 0-4 | Silty Clay/Lean Clay | Cohesion (c) = 15 kPa  Bulk Density γb= 19.0 kN/m3 |
| 4-8 | Silty Clay/Lean Clay | Cohesion (c) = 25 kPa  Bulk Density γb= 19.0 kN/m3 |
| 8-13 | Silty Clay/Lean Clay | Cohesion (c) = 50 kPa  Bulk Density γb= 19.5 kN/m3 |
| 13-40 | Silty Sand/Sand with Silt | Phi(φ) = 34o  Density (γb)=18.5 kN/m3 |

**2.3. Bhikki RLNG Power Project Site [9]**

Subsoil conditions consist of alluvial deposits comprising top layer of firm silty clay/lean clay up to thickness of 5 m followed by medium dense silty sand stratum. This stratum is followed by very stiff silty clay/lean clay. This clay stratum is underlain by dense to very dense silty sand/sand with silt. Ground water table depth varies from 1.9 to 3.15 m below existing ground level. Table 3 shows the subsoil parameters for evaluation of pile capacities.

Table 3: Design soil parameters for project testpiles location

|  |  |  |
| --- | --- | --- |
| Depth (m) | Material Type | Selected Parameters |
| 0-5 | Silty Clay/Lean Clay | Cohesion (c) = 25 kPa  Bulk Density γb= 19.0 kN/m3 |
| 5-18.5 | Silty Sand/Sand with Silt | Phi(φ) = 31.5o  Density (γb)=18.0 kN/m3 |
| 18.5-25.5 | Silty Clay/Lean Clay | Cohesion (c) = 75 kPa  Bulk Density γb= 19.0 kN/m3 |
| 25.5-45 | Silty Sand/Sand with Silt | Phi(φ) = 34o  Density (γb)=18.5 kN/m3 |

**2.4. Jhang RLNG Power Project Site [11]**

Subsoil conditions consist of alluvial deposits comprising 2 m thick top layer of very soft silty clay/silt followed by medium dense to very dense silty sand stratum. Ground water table depth varies from 2 to 4.6 m below existing ground level. Table 4 shows the subsoil parameters for evaluation of pile capacities.

Table 4: Design soil parameters for project testpiles location

|  |  |  |
| --- | --- | --- |
| Depth (m) | Material Type | Selected Parameters |
| 0-2 | Silty Clay/Silt | Cohesion (c) = 5 kPa  Bulk Density γb= 17.5 kN/m3 |
| 2-5.5 | Silty Sand | Phi(φ) = 28o  Density (γb)=16.8 kN/m3 |
| 5.5-19.25 | Silty Sand | Phi(φ) = 30.5o  Density (γb)=17.3 kN/m3 |
| 19.25-29.25 | Silty Sand | Phi(φ) = 32o  Density (γb)=17.5 kN/m3 |
| 29.25-40 | Silty Sand | Phi(φ) = 33.5o  Density (γb)=18.5 kN/m3 |

**3. Pile Construction Methods Used**

**3.1. Dry Method of Construction**

The dry method of drilled shaft construction is usually employed in those types of soils that will not cave-in during and after drilling. Soils of this nature include stiff clays, soft and hard rock, and some sands with silt, cementation aging effects etc. The wet ground conditions or presence of GWT at shallow depth prevented the use of dry boring. Rotary Bucket Auger (RBA) is an example of this method that has been used for testpile construction in dry conditions at Metro Electric Train project sites. This type of boring in the strata of Lahore, has been the first ever experience for drilled shafts construction in bulk.

**3.2. Wet Method of Construction**

When caving soils exist below the water table or are too deep, wet method is used for drilling. Plain water, bentonite or other polymeric compounds are used for fluid circulation. Reverse Rotary with water and bentonite have been used for boring in wet conditions for testpiles construction for Metro Electric Train project. Whereas both the Rotary Bucket Auger (RBA) with bentonite and Reverse Rotary (RR) with water/bentonite have been used as boring methods for testpiles construction at power projects sites.

**4. Prediction vs. Performance in Load Tests**

Following Table 5 provides summary of interpretation of all pile load tests [6, 8, 10, 12].

Table 5: Summary of pile load tests interpretation results

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Location | Test Pile No. | Test Load (kN1) | Pile Geometry | | Settlement (mm) | | Interpretation Allowable Load, Qa (FOS=2) in kN1 | | | | | |
| Length (m) | Dia. (m) | Gross | Net | Tangent Method | Limit Value Method | Chin Method | 80%, Hansen Method | 90%, Hansen Method | Avg. Load |
| Lahore | TP-1 | 10000 | 30 | 1.2 | 89.07 | 85.62 | 4750 | 2500 | 2500 | - | - | 3250 |
| TP-2 | 8000 | 22 | 1.2 | 8.02 | 5.15 | NA2 | NA | NA | - | - | 4000 |
| TP-3 | 8000 | 22 | 1.2 | 8.98 | 5.85 | NA | NA | NA | - | - | 4000 |
| TP-4 | 10000 | 40 | 1 | 31.65 | 22.83 | 4750 | 4630 | 5000 | - | - | 4790 |
| TP-5 | 10000 | 30 | 1.2 | 7.59 | 1.37 | NA | NA | NA | - | - | 5000 |
| TP-6 | 10000 | 30 | 1.2 | 46.6 | 38.65 | 4900 | 3750 | 4560 | - | - | 4400 |
| TP-8 | 10000 | 30 | 1.2 | 76.5 | 71 | 4750 | 3850 | 4350 | - | - | 4320 |
| TP-9 | 10000 | 30 | 1.2 | 14.75 | 9.9 | NA | NA | NA | - | - | 5000 |
| TP-10 | 10000 | 40 | 1 | 91.78 | 79.06 | 4700 | 3400 | 3770 | - | - | 3960 |
| TP-11 | 10000 | 22 | 1.2 | 24.98 | 17.27 | 4900 | 4700 | 5000 | - | - | 4870 |
| TP-12 | 12000 | 35 | 1.2 | 71.39 | 62.26 | 5750 | 4400 | 4950 | - | - | 5030 |
| TP-13 | 10000 | 30 | 1.2 | 124.4 | 116.2 | 3880 | 2750 | 3170 | - | - | 3270 |
| TP-14 | 8000 | 22 | 1.2 | 11.76 | 4.71 | NA | NA | NA | - | - | 4000 |
| TP-153 | 7000 | 22.4 | 1.2 | 82.61 | 78.94 | 1325 | 980 | - | - | - | 1152.5 |
| Balloki | TP-1 | 5970 | 30 | 0.76 | 11.073 | 3.29 | NA | NA | NA | NA | NA | 2985 |
| TP-2 | 10200 | 30 | 0.76 | 74.53 | 56.73 | 4950 | 3875 | 5100 | NA | NA | 4640 |
| TP-3 | 6120 | 20 | 0.76 | 42.05 | 30.55 | 2950 | 2675 | NA | 3095 | NA | 2910 |
| TP-4 | 6120 | 20 | 0.76 | 114.65 | 104.87 | 2300 | 1725 | 2935 | 2600 | NA | 2390 |
| TP-5 | 10200 | 30 | 0.76 | 99.92 | 74.095 | 4800 | 3400 | NA | NA | NA | 4100 |
| TP-9 | 10200 | 30 | 0.76 | 92.125 | 77.945 | 4875 | 3000 | NA | NA | NA | 3940 |
| TP-10 | 6690 | 30 | 0.76 | 117.72 | 109.58 | 3000 | 2150 | NA | NA | NA | 2575 |
| TP-11 | 10200 | 30 | 0.76 | 81.42 | 66.71 | 4900 | 2800 | NA | NA | NA | 3850 |
| TP-12 | 6120 | 20 | 0.76 | 112.7 | 104.20 | 2300 | 1600 | 2895 | 2615 | NA | 2352.5 |
| Bhikki | TP-1 | 4500 | 30 | 0.76 | 4.848 | 1.215 | 2250 | 2250 | 2250 | 2180 | 2250 | 2240 |
| TP-2 | 4850 | 26.5 | 0.76 | 9.26 | 2.41 | NA | NA | NA | NA | NA | 2425 |
| TP-3 | 4500 | 26.5 | 0.76 | 8.99 | 2.07 | NA | NA | NA | NA | NA | 2250 |
| TP-6 | 4780 | 26.5 | 0.6 | 13.18 | 5.31 | NA | NA | NA | NA | NA | 2390 |
| TP-7 | 5210 | 26.5 | 0.6 | 23.37 | 9.64 | NA | NA | NA | NA | NA | 2605 |
| Jhang | TP1-3 | 6250 | 30 | 0.76 | 116.9 | 107.33 | 2850 | 1500 | - | - | 3250 | 2530 |
| TP1-4 | 4800 | 30 | 0.76 | 119.6 | 112.31 | 2000 | 1150 | - | - | 2400 | 1850 |
| TP1-5 | 6250 | 30 | 0.76 | 115.32 | 107.94 | 2575 | 1750 | - | - | 3100 | 2480 |
| TP-2-1 | 2140 | 20 | 0.6 | 90.51 | 84.85 | 800 | 400 | - | 1420 | 1100 | 930 |
| TP-2-2 | 2400 | 20 | 0.6 | 93.94 | 89.23 | 900 | 550 | - | - | 1250 | 900 |
| TP-2-3 | 3980 | 20 | 0.6 | 96.23 | 84.53 | 1700 | 875 | - | - | 2000 | 1525 |

1 Converted from tons to kN using 1 ton=10 kN, 2 Not Applicable, as interpretation is not possible

Drilled shafts capacities in compression were predicted by the use of method as specified by NAVFAC Design Manual 7.02 [13]. Ultimate pile load tests were performed to determine the ultimate load carrying capacity of testpiles. Most of these tests carried were taken to yielding stage to determine the load vs. settlement behavior before failure. Load tests on all the testpiles of projects under current study were carried out according to the ASTM D1143 M-07 standard procedure. Tangent method, Chin Method, Davisson Limit Value Method, 80% and 90% Hansen Methods were used for interpretation of pile load test results [14-15]. Table 6 shows the comparison of values of predicted allowable load and interpreted loads with estimate of over/under prediction.

Table 6: Comparative Values of Predicted Allowable and Interpreted Loads [6, 8, 10, 12]

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Location | Testpile No. | Drilling Method | Drilling Fluid | Predicted Allowable Load (kN) | Test Load (kN) | Percentage of Design Load | Interpreted Allowable Load (kN) | Over/under Prediction  (-/+) % |
| Lahore | TP-1 | RRa | water | 4000 | 10000 | 2.5 | 3250 | -19 |
| TP-2 | RBAb | - | 2830 | 8000 | 2.8 | d Not Yielded(>4000) | >40 |
| TP-3 | RBA | - | 2830 | 8000 | 2.8 | Not Yielded(>4000) | >40 |
| TP-4 | RR | water | 4000 | 10000 | 2.5 | 4790 | +20 |
| TP-5 | RR | water | 4000 | 10000 | 2.5 | Not yielded(>5000) | >25 |
| TP-6 | RR | water | 4000 | 10000 | 2.5 | 4400 | +10 |
| TP-8 | RR | water | 4000 | 10000 | 2.5 | 4320 | +8 |
| TP-9 | RR | water | 4000 | 10000 | 2.5 | Not yielded(>5000) | >25 |
| TP-10 | RR | water | 4000 | 10000 | 2.5 | 3960 | -1 |
| TP-11 | RBA | - | 2830 | 10000 | 3.5 | 4870 | +72 |
| TP-12 | RR | water | 4750 | 12000 | 2.5 | 5030 | +6 |
| TP-13 | RR | water | 4000 | 10000 | 2.5 | 3270 | -18 |
| TP-14 | RBA | - | 2830 | 8000 | 2.8 | Not yielded(>400) | >40 |
| TP-15c | RR | Bentonitec | 2850 | 7000 | 2.6 | 1150 | -60 |
| Balloki | TP-1 | RBA | Bentonite | 1990 | 5970 | 3.0 | Not yielded (>2985) | >50 |
| TP-2 | RBA | Bentonite | 1990 | 10200 | 5.1 | 4640 | +133 |
| TP-3 | RBA | Bentonite | 1630 | 6120 | 3.8 | 2910 | +78.5 |
| TP-4 | RBA | Bentonite | 1630 | 6120 | 3.8 | 2390 | +47 |
| TP-5 | RBA | Bentonite | 1990 | 10200 | 5.1 | 4100 | +101 |
| TP-9 | RR | Water | 1990 | 10200 | 5.1 | 3940 | +98 |
| TP-10 | RR | Water | 1990 | 6690 | 3.4 | 2575 | +29 |
| TP-11 | RR | Water | 1990 | 10200 | 5.1 | 3850 | +93 |
| TP-12 | RR | Water | 1630 | 6120 | 3.8 | 2352.5 | +44 |
| Bhikki | TP-1 | RR | Water | 1500 | 4500 | 3.0 | 2240 | +49 |
| TP-2 | RR | Water | 1500 | 4850 | 3.2 | Not yielded (>2425) | >62 |
| TP-3 | RR | Water | 1500 | 4500 | 3.0 | Not yielded (>2250) | >50 |
| TP-6 | RR | Water | 1500 | 4780 | 3.2 | Not yielded (>2390) | >59 |
| TP-7 | RR | Water | 1500 | 5210 | 3.5 | Not yielded (>2605) | >74 |
| Jhang | TP1-3 | RBA | Bentonite | 2500 | 6250 | 2.5 | 2530 | +1 |
| TP1-4 | RBA | Bentonite | 2500 | 4800 | 1.9 | 1850 | -35 |
| TP1-5 | RBA | Bentonite | 2500 | 6250 | 2.5 | 2480 | -0.8 |
| TP-2-1 | RBA | Bentonite | 1150 | 2140 | 1.9 | 930 | -19 |
| TP-2-2 | RBA | Bentonite | 1150 | 2400 | 2.1 | 900 | -22 |
| TP-2-3 | RBA | Bentonite | 1150 | 3980 | 3.5 | 1525 | +33 |

a RR: Reverse Rotary, b RBA: Rotary Bucket Auger, cUse of uncontrolled bentonite in Lahore/TP-15 only

d Not yielded: could result into more allowable load

**5. Commentary on Pile Behaviour and Reasons for Discrepancies**

The results as shown in Table 6 have indicated that drilled shaft constructed with the RR method using plain water as the drilling fluid indicate that six piles do not exhibit significant settlement leading to yielding of piles. It is therefore expected that had other these six load tests been loaded to more than the current test load, they would have resulted into more allowable load. Referring to Table 6 and Figure 1, for 25% of the data for RR drilled shafts using water as drilling fluid, where yielding has taken place, allowable load has been overpredicted ranging from 1% to 19% whereas for the remaining 75% data allowable load has been underpredicted ranging from 6% to 98%.

Drilled shafts constructed with RR method using bentonite (in uncontrolled conditions) was not able to carry the test load and yielded at 325 tons, thus making the overestimation of predicted load by 60%.

The load tests carried out on RBA drilled shafts constructed in dry condition have revealed that the three out of four load tests have not shown yielding even under 2.8 times the design load. One load test was loaded to 3.5 times the design load and has shown the interpreted allowable load to be 70% higher than the predicted load. It is therefore expected that had other three load tests been loaded to more than 800 tons, they would have yielded the allowable load of more than 400 tons. Pile load test results have indicated that the load carrying capacity of RBA drilled shafts in dry condition is far greater (1.75 times) than that of RR drilled shafts in wet condition using bentonite for the same length and diameter.

RBA drilled shafts using bentonite as the drilling fluid are showing that one drilled shaft has not shown significant settlement leading to yielding. It is therefore expected that had this been loaded to more than the current test load, this would have resulted into more allowable load, leading to higher underestimation of predicted load. 40% data indicates overestimation of predicted load by 0.8% to 35% and 60% data indicates underestimation of predicted load by 1% to 133% for drilled shafts constructed with RBA method using bentonite where yielding have taken place.

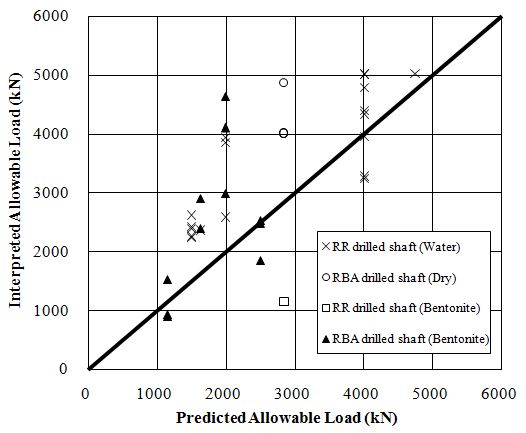


Figure 1: Predicted vs. Interpreted Allowable Loads

Referring to Table 6 and Figure 1, it reveals that underestimation of predicted load is relatively more pronounced for RBA drilled shafts using bentonite as compared to RR drilled shafts using plain water.

Comparison has also indicated that drilled shaft capacities had been grossly underpredicted for RBA method in dry condition and overpredicted for RR method using bentonite, at the design stage. It reveals that assumption of using the same pile capacities for dry RAB and RR were not correct. The test results have indicated the wide variation of pile load capacity by the all four methods of construction.

It is considered that bentonite slurry gets removed from the bore walls with the rising concrete column, if construction is done within 4-5 hrs. If slurry remains in the hole for too long, the bentonite cake can become stiff and thick, which is difficult to be removed with the rising concrete. The thicker the slurry layer, the more likely is that the slurry will not get properly removed. Slurry remains on the bore wall excessively reduce the side resistance of a drilled shaft [16].

**6. Conclusions and Recommendations**

Following are the major conclusions and recommendations:

1. Drilled shafts construction using the dry method has the least disturbance effect on the soil around drilled shaft. The amount of error involved with pile drilling increases when water or some slurry is introduced to the hole.
2. RBA drilled shafts in dry condition yields higher load bearing capacity where as RR drilled shafts using bentonite yield lower load bearing capacity.
3. If slurry remains in the hole for too long, the bentonite cake can become stiff and thick. The thicker the slurry cake, the more likely is that the slurry will not get properly removed. Slurry remains on the bore wall excessively reduces the side resistance, leading to reduced load bearing capacity of drilled shaft.
4. The use of bentonite slurry should be conditional with very strict control over its specific gravity and time for construction, after completion of bore.
5. Underestimation of predicted loads are relatively more pronounced for RBA drilled shafts using bentonite as compared to RR drilled shafts using plain water.
6. Pile load test must be a mandatory requirement for finalizing the design of drilled shaft for each boring method.
7. It is recommended to adjust parameters for designing drilled shafts to be constructed by all four boring methods for similar ground conditions.

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