Comparison of pile dynamic and static load tests in clayey deposits of Southwest Iran with special attention on soil setup

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Abstract

It is well known that driven piles in clayey deposits typically undergo a time-dependent increase in capacity following initial installation due to "soil setup". The static and the dynamic pile testing methods are the two main types of pile tests that are periodically used to assess the pile load capacity and setup measurement. The main objective of this study is to compare the static and dynamic load tests results and to evaluate the ability of the High Strain Dynamic Test (HSDT) using CAPWAP method to estimate the static capacity of driven piles and setup measurement. This paper compiles the test results of HSDT and SLT at two piling project sites within clayey deposits of Southwest Iran. Evaluation of the test results indicates that shaft resistance has considerably increased over time at the study sites. Examination of the full scale static load test data and CAPWAP analyses suggested that HSDT could provide a suitable tool to assess static driven pile capacities. The dynamic load pile test, which is a simple quality control test offering a considerable savings of time and cost and requires less space, can be used for predicting pile capacity and pile integrity under proper care and it should be calibrated by static tests.

Keywords: Clayey Deposits, Pile Bearing Capacity, Dynamic Load Test, Static Load Test.

1. Introduction

Driven pile foundations are used to transfer the superstructure loads to the ground deep enough in order to prevent excess settlement. Estimation of axial capacity plays an important role in foundation design. The prediction of pile bearing capacity can be achieved using different methods such as static and dynamic load tests, static analysis and direct methods based on in situ tests [1]. One of the important issues in driven piles is variation of bearing capacity with time after the initial drive. It is well known that driven piles in clayey deposits typically undergo a time-dependent increase in capacity following initial installation due to "soil setup" [2], [3]. The static and the dynamic pile testing methods are the two main types of pile tests that are periodically used to assess the pile load capacity and setup measurement .

Ordinary static pile load tests using kentledge or reaction piles are used in Iran. Owing to increasing time and cost, particularly with the difficulties associated with transporting static load testing accessories into congested city centers and the lack of space on many sites, contractors are seeking an alternative system for pile testing. The tendency is for contractors to use dynamic techniques in order to supplement ordinary static tests. Dynamic pile load testing also known as High Strain Dynamic Testing (HSDT) was introduced in Iran in the later part of nineties and became popular 2002 onwards. This test is faster and more convenient than SLT and also offers significant cost savings especially for higher capacity piles. Although there are many applications for dynamic pile testing, bearing capacity being the main one. The ability to accurately predict static capacity from dynamic pile testing has resulted in many studies, and has been the focus of dynamic pile tests on many project sites. Likins and Rausche (2004) have reported that the pile capacity tested using HSDT correlated well with the static load test results [4]. Gue and Chen (1998) showed that HSDT has over predicted the pile capacity by more than 60% [5]. They commented that HSDT could only be an effective mean of construction control. Attar and Fakharian (2013) Compared SLT and DLT results by considering soil setup effect. They conducted that compensating the time differences of performing SLTs and HSDTs is an important issue in analyzing DLT Results [6]. However, there is still lack of good understanding among the geotechnical engineers on the wave equation theory in HSDT tests.

This study is aimed to compare the Dynamic Load Tests (DLT) at EOD and BOR with pile Static Load Tests (SLT). Two queries and their answers serve as a prime objective to this paper: (i) Do SLT and HSDT produce similar pile capacity? (ii) Does HSDT truly simulate static load displacement behavior of a pile? For this purpose, this paper presents the case histories of the high strain dynamic pile load tests (HSDT) and static pile load tests (SLT) carried out at two piling project sites within clayey deposits of Southwest Iran based on the well documented test results.

2. CASE HISTORIES

In order to illustrate the application of HSDT and its comparison with SLT results, the following two case histories are chosen.

Case 1: Arvand Jahan Ara Steel, Khuzeatan, Iran

Arvand Jahan Ara Steel (AJS) Making Plant area is located near Khoramshahr city in Khuzestan province, Iran. The underlying subsoil generally consist of clayey layers with alternates of silt and sand. A detailed field testing program was planned for the 400 × 400 mm square driven piles including dynamic load testing (PDA), CAPWAP analysis, and static load testing. The "Pile Testing Program" on 18 "Test Piles" (TP) across the project site was carried out from September 02, 2015 through October 16, 2015. The test piles were all 400 mm precast concrete square piles with two segments spliced by bolting. The embedment depths are in the range of 15.7 m to 22 m. All piles were driven by a Delmag 32-46 single-acting diesel hammer. All piles were tested both at "End Of Initial Drive" (EOID) and "Beginning of Restrike" (BOR) condition by PDA equipment. Static load test performed on four piles D-TP1 through D-TP4.

The pile installation records of the four test piles shown in Figure 1 indicate consistency between the blow count profile and SPT'N and CPTu profile of the adjacent boreholes.

Case 2: BIDBOLAND II Gas Refinery, Khuzeatan, Iran

BIDBOLAND II Gas Refinery project is located near Mahshahr city in Khuzestan province, Iran. Soil layers in the study area generally consist of clayey layers. A detailed field testing program was planned for the Pre-stressed close-end spun concrete piles with the circular outer diameter of 450 and 600 mm including dynamic load testing (PDA), CAPWAP analysis, and static load testing. The "Pile Testing Program" on 28 "Test Piles" across the project site was carried out from February 24, 2016 through March 30, 2016. The test piles were 450 and 600 mm close-end spun piles with two or three segments spliced by welding. The embedment depths are in the range of 21.4 to 33.2 m. All piles were driven by a Delmag 32-46 single-acting diesel hammer. All piles were tested both at "End Of Initial Drive" (EOID) and "Beginning of Restrike" (BOR) condition by PDA equipment. Static load test performed on three piles C3A-TP5, C4A-TP5 and C5A-TP5.
The pile installation records shown in Figure 2 indicate good agreement in the driving resistance of the test piles to soil consistency of the respective adjacent boreholes.

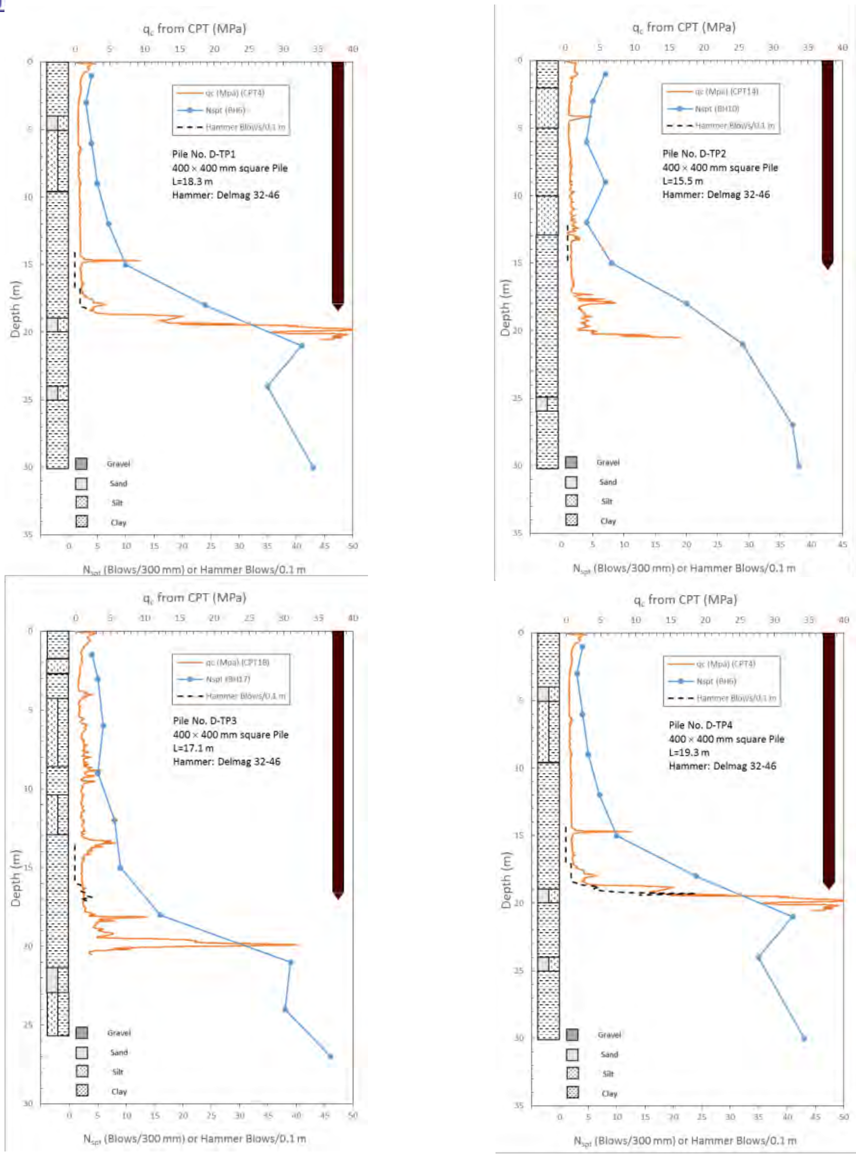

Figure 1. SPT'N and CPTu profile with pile installation records <u>(Case 1)</u>

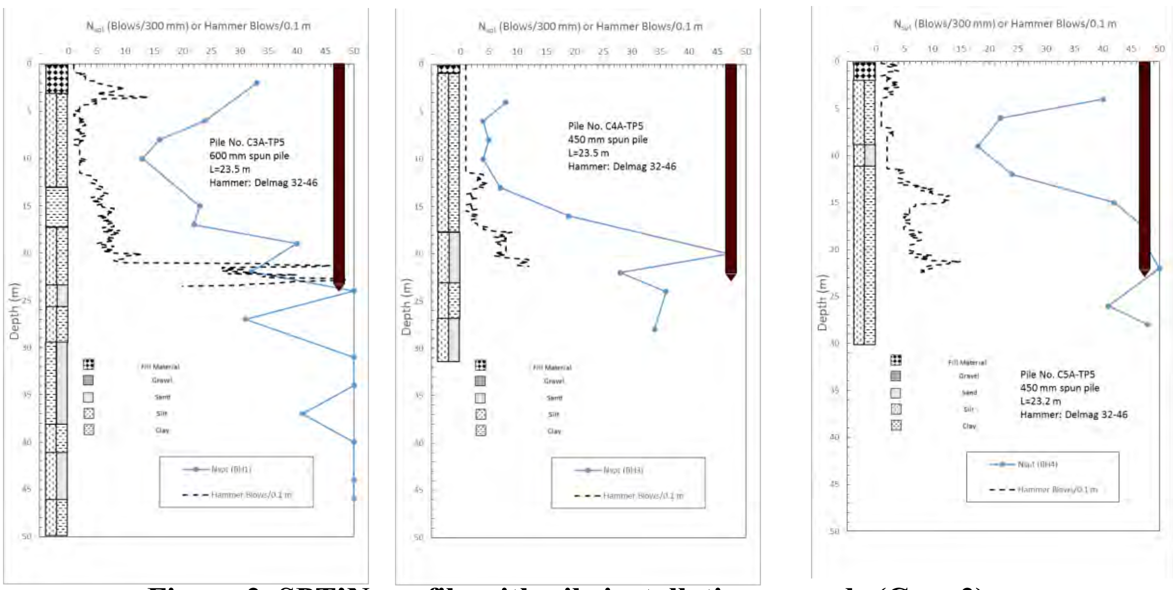

Figure 2. SPT'N profile with pile installation records <u>(Case 2)</u>

3. TESTING METHODOLOGY

Dynamic testing of pile (PDA test) is based on the analysis of one dimensional waves generated when the piles was hit by a suitable hammer. Therefore, for the purpose of testing, the pile must be hit (re-strike if the pile has been driven) by a hammer capable to transfer sufficient impact energy to mobilize the pile capacity. Two types of sensors, namely vibrating wire strain gauges and accelerometer were installed at 2 times the pile diameter below the top of the pile. Pile Driving Analyzer (PDA) was used for recording forces and motion after each drop of hammer. For EOID tests, the gages were installed from beginning of diesel hammer driving towards the target embedment depth, to monitor the driving stresses, hammer performance, and variation of capacity with depth. For Restrike tests, the gages were installed and a limited number of blows were applied to measure the BOR capacity. The penetration per blows was monitored using theodolite readings to obtain the exact set for further analysis purposes. To obtain a reliable ultimate capacity from dynamic testing, some guideline must be followed, such as hammer weight, impact factor, a few of them are mentioned, to mobilize the full soil strength. The minimum suggested hammer weight 1% of the required ultimate pile capacity to be proved for shafts installed in soils, and for the piles with larger expected end bearing contributions, the recommended percentage increases to at least 2% of the ultimate pile capacity to be tested.

The measurement were recorded by PDA test and analyzed with the well-known “Case Method” using the Case Pile Wave Analysis Program (CAPWAP) software. Procedure for conducting the PDA test is presented in ASTM 4945 Standard Test Method for High Strain Dynamic Testing of Deep Foundation.

For static load test (SLT), four-pile reaction system was used as per ASTM D-1143. The reaction was provided by platform, two girders and four piles. Two 200-ton or one 400 ton hydraulic jacks were used to perform the tests with a stroke of 15 cm. The load is measured by high quality “Load Cells”. The pile head displacements were measured by four gages supported by reference beams mounted to ground at a minimum distance of 3 m from the pile head and the girder support blocks. Load test arrangement for dynamic and static load test is seen in Figure 3.

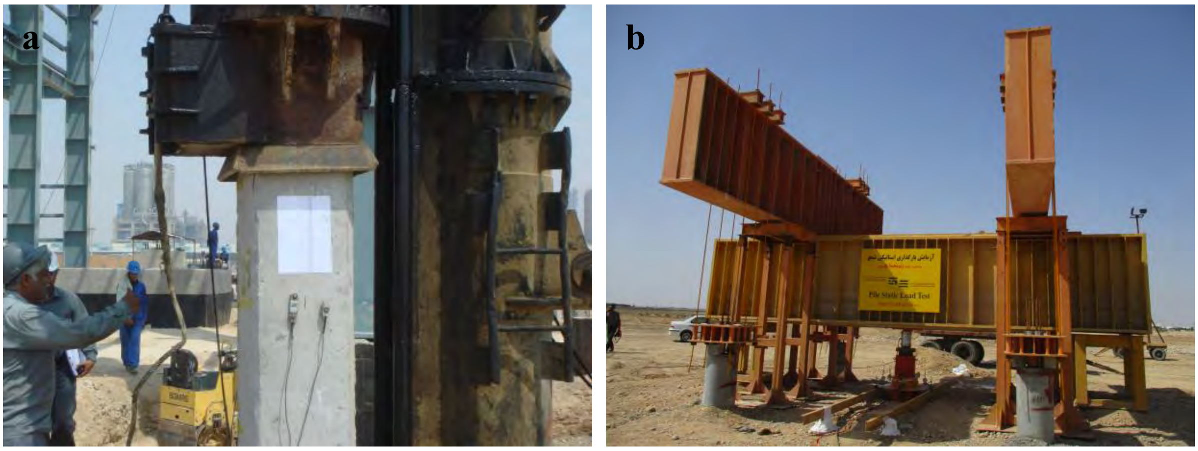

Figure 3. (a) Dynamic pile load test (b) Platform, girders and reaction set up for static axial load test.

4. DISCUSSION AND RESULTS

Figure 4 and Figure 5 reflect the comparison between the dynamic and static load test curves for the case 1 and 2 respectively. It should be noted that conducting the SLT just after EOID is not practical (impossible). However, it is interesting to compare the calculated load-displacement curves at EOID and BOR with the measured curve in the SLT to discuss the setup phenomena of the driven pile.

As seen from the figure, the stiffness of the static response derived from the BOR test is higher than that derived from the EOID test, indicating the “set-up” phenomenon discussed previously. The static response derived from the BOR test is comparable with the SLT, compared to that obtained from the EOID test. The load-displacement curves in Figure 4 and Figure 5 clearly indicate the “set-up” phenomenon during the period from the EOID test via the BOR test to the SLT. Namely, the soil resistance parameters identified from the EOID test and the BOR test reflect the effects of generation of excess pore pressures during driving and subsequent dissipation of the excess pore water pressures after EOID, in other words, the change of the effective stresses in the soil surrounding the pile

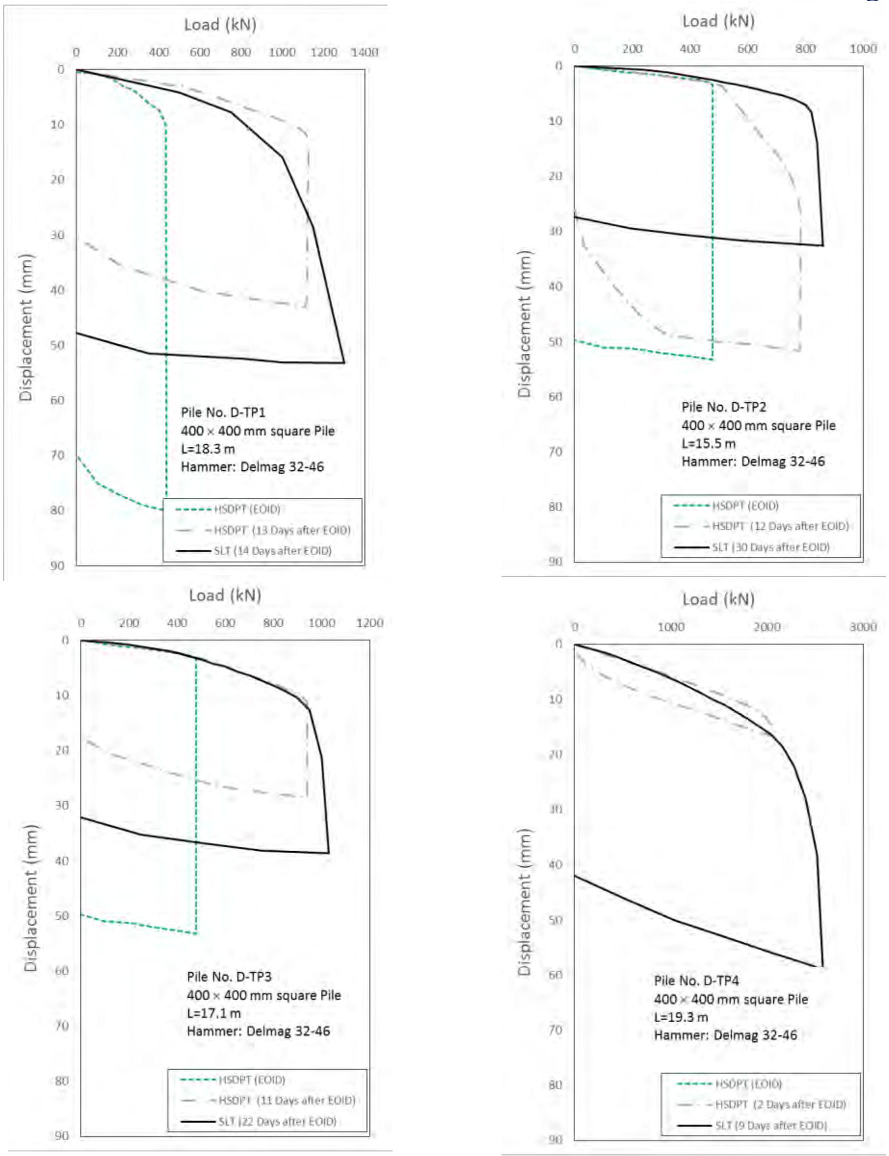

Figure 4. Load settlement behavior of Test Piles <u>(Case 1)</u>

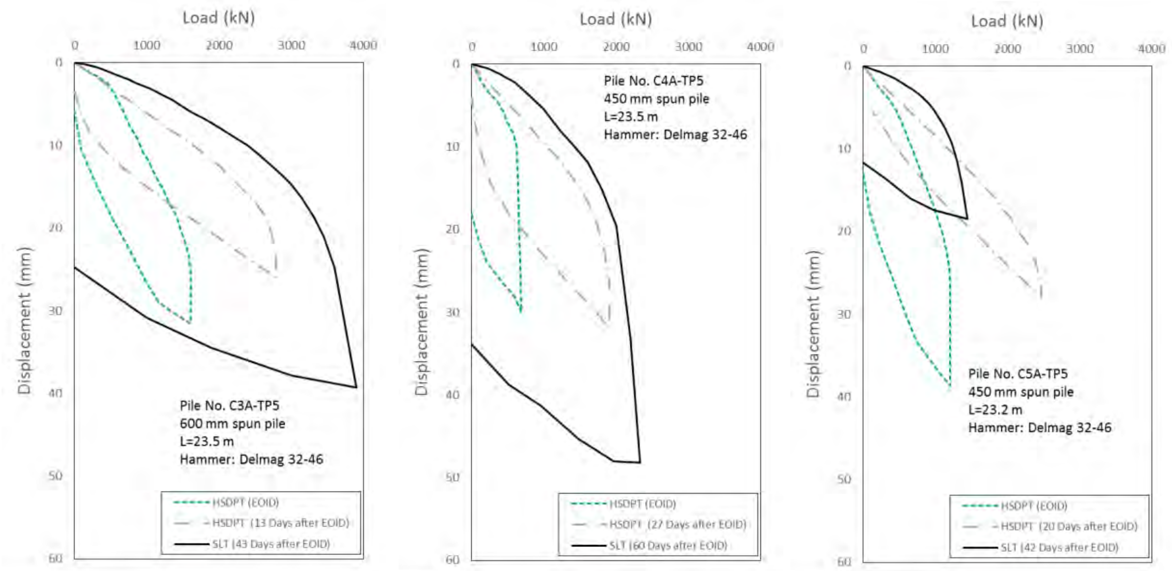

Figure 5. Load settlement behavior of Test Piles <u>(Case 2)</u>

The static and dynamic test results are presented in Table 1. Signal matching analysis using CAPWAP was used to distinguish the tip and shaft resistances of DLT tests. Davisson Offset Limit method (Davisson, 1970) was used to determine ultimate load of the pile. The results have also indicated that significant setup occurred along the pile shaft (Q_s), while the pile tip resistance (Q_b) slightly increased.

Table 1- SLT and DLT results on the "test piles"

Project	Pile No.	Pile type & size (mm)	Test Type	Day(s) After EOD	Embed. (m)	Computed Resistance (kN)			Predicted By Formula
						Shaft	Toe	Total	
AJS	D-TP1	Square 40×40 cm	EOD	0.00	18.00	125	310	435	----
			BOR	13.00	18.20	762	365	1,127	----
			SLT	14.00	18.30			1,150	1,132
	D-TP2	Square 40×40 cm	EOD	0.00	14.80	75	284	359	----
			BOR	12.00	15.50	469	313	782	----
			SLT	30.00	15.70			840	822
	D-TP3	Square 40×40 cm	EOD	0.00	16.10	109	309	419	----
			BOR	0.01	16.50	219	309	528	----
			BOR	0.21	16.80	415	317	732	----
			BOR	1.00	17.00	509	321	830	----
			BOR	11.00	17.00	668	326	994	----
			SLT	22.00	17.10			960	1,038
	D-TP4	Square 40×40 cm	BOR	2.00	19.30	1,085	997	2,082	----
			SLT	9.00	19.30			2,200	2,265
Bidboland	C3A-TP5	Spun Pile-600 mm	EOD	0.00	23.20	395	1,217	1,612	----
			BOR	13.21	23.30	1,537	1,246	2,783	----
			SLT	43.00	23.50			3,428	3,165
	C4A-TP5	Spun Pile-450 mm	EOD	0.00	21.30	224	406	630	----
			BOR	27.42	21.42	1,285	626	1,910	----
			SLT	60.00	23.50			2,000	2,051
	C5A-TP5	Spun Pile-450 mm	EOD	0.00	23.00	321	888	1,209	----
			BOR	1.08	23.00	793	950		----
			BOR	8.06	23.00	1,197	890		----
			BOR	20.15	23.10	1,394	1,000	2,394	----
			SLT	48.00	23.20			2,845	2,750

Figure 6 shows the comparison of interpreted pile capacity of the aforementioned test piles from HSDT and SLT results. The interpreted pile capacity of the test piles from these well-documented load test results at two piling sites in Iran are in reasonably fair agreement with the results of static load tests. It is noticed that in most cases the ultimate capacity obtained from SLT is greater than the HSDT results. It is reminded that a Delmag 32-46 single-acting diesel hammer has been used for restrike tests, having sufficient energy to mobilize the ultimate capacity. The main reason of underestimating the capacity in HSDT results is differences in testing time. Most SLTs were performed after a longer time compared to HSDT. At the time of PDA tests, soil setup effects have not been completed yet. To compensate for the difference in test times, the skin friction of PDA test results has been predicted using the empirical relation proposed by Skov and Denver (1988). In this relation, the effect of soil set-up is considered to be a function of time logarithm as shown in Equation 1.

$$Q_t/Q_0 = 1 + A[\log(t/t_0)] \qquad (1)$$

Where: Q_t = pile ultimate load at time t (shaft load in this study); Q_0 = pile ultimate load at time t_0 (shaft load in this study); A = a factor dependent on soil type; t_0 = a reference time.

It should be noted that t_0 is a function of soil type, and pile size. Using prestressed concrete piles and H-piles, Camp and Parmar (1999) empirically determined to equal to 2 days, but stated that t_0 equal to 1 day seems to be reasonable. Svinkin et al. (1994) used t_0 equal to 1 to 2 days. Bullock (1999), and McVay (1999), recommend standardizing to equal to 1 day.

The setup factor, A back-calculate from DLT results at different times from EOID. Having used signal matching analysis, the tip and shaft resistances are distinguished first. Then $Q_{s,t}/Q_{s,t0}$ for corresponding t/t_0 is calculated for each pile, out of which A has been determined using Skov and Denvor relation. The variations of normalized shaft capacity ($Q_{s,t}/Q_{s,t0}$) with respect to $\log(t/t_0)$ for D-TP3 (Case1) and C5A-TP5 (Case2) are plotted in Fig. 7. setup factor is equal to 0.28 and 0.6 on case1 and case2 respectively.

Skin friction for the time difference between DLT and SLT has been calculated and added to PDA predictions. The corrected capacity is referred to as "modified dynamic test". The modified results are presented in Fig. 8. A much better correlation is observed between SLTs and DLTs, after the time difference modifications.

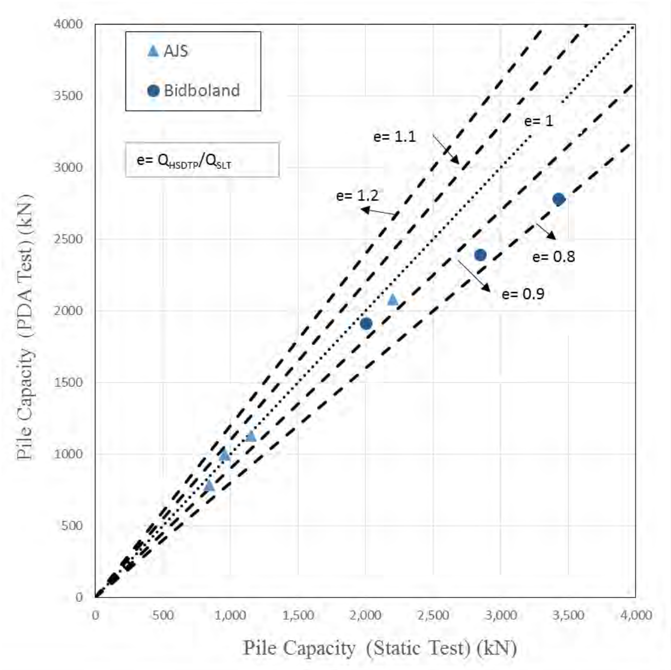

Figure 6. Comparison of static (SLT) and dynamic (DLT) test results

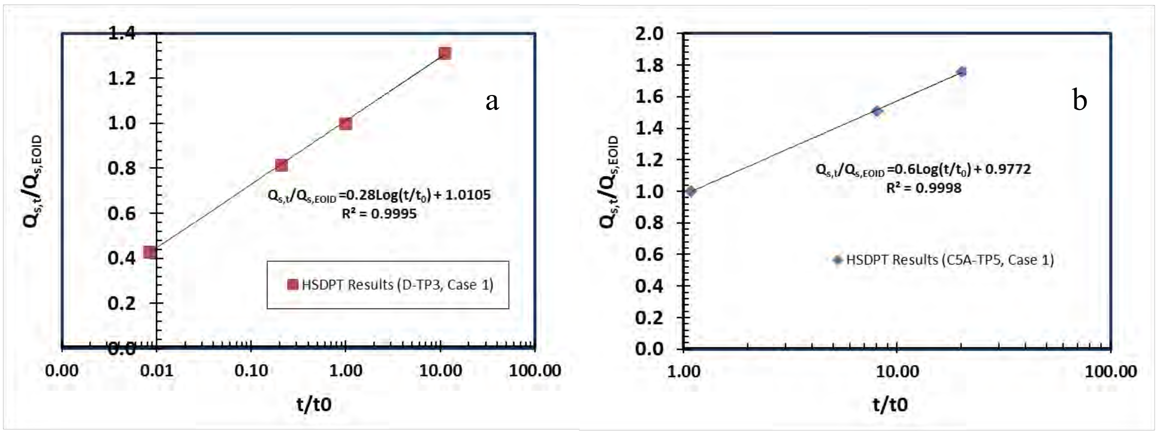

Figure 7. Setup factor (a) for Case 1 b) for Case 2

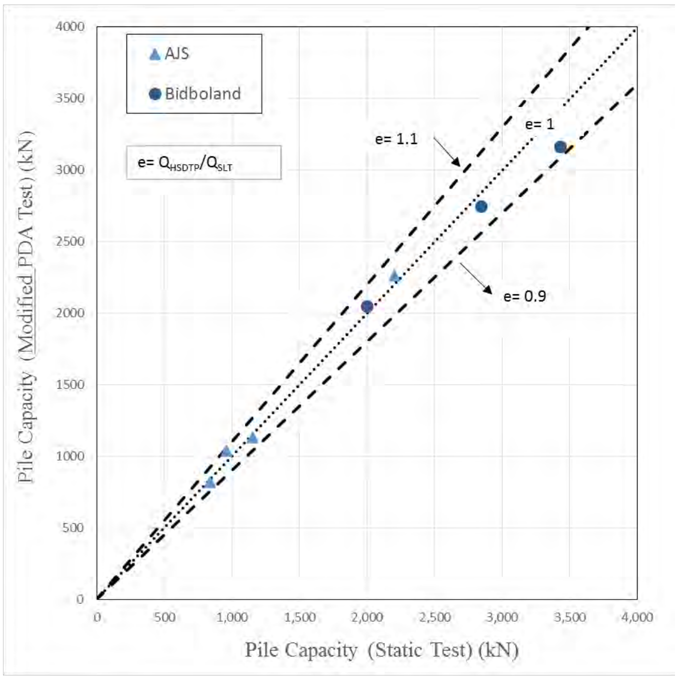

Figure 8. Comparison when modification on soil setup effects are done on dynamic tests

9. CONCLUSIONS

Dynamic load test is commonly carried out as an alternative to ordinary static load test owing to high cost and time consuming of the static load test. Also, pile integrity assessment is an additional advantage of dynamic load test. In Iran, HSDT is gaining increasing popularity and is being used extensively to estimate the pile capacities and integrity. It then becomes necessary to evaluate its ability to produce similar results to that of SLT. However, this task is not straight forward and involves many complex issues including testing the same pile twice, testing adjoining piles, time effects, errors associated with testing, expertise of the test engineers etc. Literatures have indicated close agreement between field static and dynamically computed ultimate loads. Correlation studies between static and dynamic tests help in building more confidence in HSDT and also checks the capability of the testing agency.

This paper discusses the reliability of dynamic tests by comparing the results of dynamic and static tests on piles from the same site. The following conclusions are drawn.

1. The stiffness of the static response derived from the BOR test is higher than that derived from the EOID test due to "set-up" phenomenon. The static response derived from the BOR test is comparable with the SLT, compared to that obtained from the EOID test.
2. Comparison between SLT and DLT results at first has shown that capacity obtained from SLT was greater than the dynamic test results, but with compensating the time differences of performing SLTs and DLTs, a much better correlation was obtained.
3. The pile setup estimation methods proposed by Skov and Denver (1988) were shown to be satisfactory for specific soil types. Dynamic loading test at different time intervals after EOID can be used to determine the setup factor.
4. Generally, HSDT can provide an effective mean of predicting pile capacity, establishing termination criteria for pile installation and construction control if calibration against SLT is properly carried out. For pile capacity prediction, restriking test after the pile installation is generally recommended. The duration of resting before restriking test will depend on soil type.
5. In order to obtain a meaningful diagnosis of pile conditions, data acquisition, data processing and interpretation are the key factors during the HSDT implementation. Otherwise, the HSDT results can lead the foundation designer to make an unsound engineering decision.

10. ACKNOWLEDGMENT

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